A conceptual model of a sustainable system based upon observations of biodegradable plastic packaging film experiments and material flow

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Abstract

One can imagine full knowledge of a system allows for optimal decision making when problems arising within that system need to be solved. In reality, solutions involving any non-trivial system must be pursued with incomplete knowledge. In light of the complexity and diversity of current industrial economic systems and the decision-making processes pertaining to them, integrating streams of knowledge would improve problem solving outcomes on such scales. More specifically, it could potentially address how to compare the rate of problem proliferation to solution implementation within a system. However, successfully integrating knowledge of diverse systems towards a common purpose requires careful and consistent analogies to be constructed between the entities of those systems. The current work investigates the merits of such an approach for resolving sustainable development issues. The hypothesis is that knowledge of what influences the flow and transformation of matter, (that is, what influences a common phenomenon throughout life-supporting systems), can facilitate this integration. The problem of accumulating material waste is used as a vehicle to focus the discussion.

To this end, the foundation of the work is an experimental study into the development of a starch based biodegradable plastic packaging film. The two main constraints on sample production were to minimise cost and maximise biodegradability. Slit die rheological data is gathered for five samples selected from polymer extrusion trials as part of describing their viscous behaviours via a semi-empirical model incorporating die temperature (measured at 120, 140 and 160°C) and shear rate (altered by screw speeds of 5-50 rpm). The samples differ in additive content and extrusion passes from a baseline starch/water/glycerol (~73/18/9.0 wt% total) combination extruded once to the addition of cross-linking agents and surface modifiers (<1 wt% total) extruded twice. GPC, DSC, tensile strength and moisture absorption analyses join the rheological data to explain observed flow behaviour in terms of the influence of sample constituents, processing conditions and the ensuing molecular transformations. Regression coefficients, $R^2$, between 0.957 and 0.981 are obtained for model predicted viscosity versus observed viscosity suggesting a satisfactory fit of the model for the five samples within the experimental parameters.

The experimental study represents a typical analytical approach to developing a technical solution. Yet while technology will remain indispensable to problem solving, there is a
need to realise that splintering knowledge into disciplines of the ever finer detail required to extend technical accomplishment, must also be complemented by a synthesis of associated facts and relevant theories to address more encompassing problems associated with sustainability of the modern industrial economy. Therefore, considering the relative success of modelling the viscous behaviour of the starch based plastic samples, it was proposed to extend the concepts of rheology used to explain the flow of matter on the molecular scale to the flow of matter on the scale of the industrial economy. To whatever extent possible, the advantages of being able to predict how such flows respond to industrial economic decisions would contribute to the research of sustainable systems.

The assumption is made here that an apt material flow undergirds a sustainable system. A conceptual model is constructed based on this assumption that aims to simplify the impediments associated with mediating the complexity of the industrial economic system with an ecologically sustainable one. Ultimately, a system is described in which a fundamental unit, or monad, is defined composed of a set of resource entities, a set of product entities, and the set of process entities that transforms the former to the latter over time. Extrapolating this monad description to define humanity as the set of process entities, any system can then be defined as a nexus of three flows: matter/energy, knowledge/information/data and money/value, where matter/energy forms the set of resource entities and money/value forms the set of product entities. Aspects of the model are demonstrated by applying it to parts of the experimental study and to the operation of a material reuse business.

The model has immediate practical benefit as a framework for organising information for the purpose of assessing and developing the sustainability of a system. It has further potential as a basis for a mathematical model that could take advantage of well-defined techniques of analogy and system integration to assist in determining the ratio between the rate of problem proliferation and the rate of solution implementation within a complex system.
Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

Journal articles
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Conference proceedings
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Contributions by others to the thesis
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Statement of parts of the thesis submitted to qualify for the award of another degree
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ANZSRC code: 090408, Rheology 30%
ANZSRC code: 091209, Polymers and Plastics 30%

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FoR code: 0904, Chemical Engineering 30%
FoR code: 0912, Materials Engineering 30%
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ASX</td>
<td>Australian stock exchange</td>
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<tr>
<td>BUR</td>
<td>Blow up ratio</td>
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<tr>
<td>CY</td>
<td>Calendar year</td>
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<tr>
<td>DMSO</td>
<td>dimethyl sulphoxide</td>
</tr>
<tr>
<td>DSC</td>
<td>Differential scanning calorimetry</td>
</tr>
<tr>
<td>DSEWPC</td>
<td>Department of Sustainability, Environment, Water, Population and Communities</td>
</tr>
<tr>
<td>EEIO</td>
<td>Environmentally-extended input-output analysis</td>
</tr>
<tr>
<td>EF</td>
<td>Ecological footprint</td>
</tr>
<tr>
<td>ESD</td>
<td>Ecologically sustainable development</td>
</tr>
<tr>
<td>GPC</td>
<td>Gel permeation chromatography</td>
</tr>
<tr>
<td>GREENSCOPE</td>
<td>Gauging Reaction Effectiveness for the Environmental Sustainability of Chemistries with a multi-Objective Process Evaluator</td>
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<tr>
<td>GRI</td>
<td>Global Reporting Initiative</td>
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<tr>
<td>HDPE</td>
<td>High density polyethylene</td>
</tr>
<tr>
<td>IChemE</td>
<td>Institute of Chemical Engineers</td>
</tr>
<tr>
<td>IISD</td>
<td>International Institute for Sustainable Development</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<tr>
<td>LCA</td>
<td>Life cycle assessment or life cycle analysis</td>
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<tr>
<td>LCC</td>
<td>Life cycle costing</td>
</tr>
<tr>
<td>LCI</td>
<td>Life cycle inventory</td>
</tr>
<tr>
<td>LCIA</td>
<td>Life cycle impact assessment</td>
</tr>
<tr>
<td>LDPE</td>
<td>Low density polyethylene</td>
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<tr>
<td>LLDPE</td>
<td>Linear low density polyethylene</td>
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<tr>
<td>LCSA</td>
<td>Life cycle sustainability analysis</td>
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<tr>
<td>MCDA</td>
<td>Multiple criteria decision analysis</td>
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<tr>
<td>MIPS</td>
<td>Material-input-per-service</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal solid waste</td>
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<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
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<tr>
<td>OPP</td>
<td>Oriented polypropylene</td>
</tr>
<tr>
<td>PACIA</td>
<td>Plastics and Chemicals Industries Association</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>PP</td>
<td>Polypropylene</td>
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<tr>
<td>PS</td>
<td>Polystyrene</td>
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<td>PVC</td>
<td>Polyvinyl chloride</td>
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<tr>
<td>RA</td>
<td>Resource acquisition</td>
</tr>
<tr>
<td>RTP</td>
<td>System of resources, processes and products</td>
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<tr>
<td>SD</td>
<td>Sustainable development</td>
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<tr>
<td>SDI</td>
<td>Sustainable development indicator</td>
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<tr>
<td>SED</td>
<td>Specific energy delivered</td>
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<tr>
<td>SLCA</td>
<td>Societal life cycle assessment</td>
</tr>
<tr>
<td>SME (in chapter 2)</td>
<td>Small and medium-sized enterprises</td>
</tr>
<tr>
<td>SME (in chapter 3)</td>
<td>Specific mechanical energy (Whr/kg)</td>
</tr>
<tr>
<td>TBL</td>
<td>Triple bottom line</td>
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<tr>
<td>TPS</td>
<td>Thermoplastic starch</td>
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<tr>
<td>TSTMP</td>
<td>Trisodium trimetaphosphate</td>
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<tr>
<td>TUR</td>
<td>Turn up ratio</td>
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<tr>
<td>USDOC</td>
<td>United States Department of Commerce</td>
</tr>
<tr>
<td>WCED</td>
<td>World Commission on Environment and Development</td>
</tr>
<tr>
<td>WRAP</td>
<td>Worldwide Responsible Accredited Production</td>
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**List of symbols**

- **d**: rate of deformation tensor
- **$E_a$**: activation energy (J/mol)
- **$F_L$**: drawdown force (N)
- **$H$**: height of slit or film thickness (m)
- **$H_L$**: final film thickness
- **$K$**: consistency index (Pa.s$^n$)
- **$K'$**: empirical constant used for modifying $K$ in Eq. 6.5 to account for an Arrehenius relationship with temperature (Pa.s$^n$)
- **$K_n$**: knowledge
- **$L$**: length of slit (m)
- **$M$**: moisture content (wt%) in Eq. 4.10
- **$m$**: modified flow index in Eq. 6.7 (dimensionless)
- **$n$**: flow index (dimensionless)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>P</td>
<td>pressure measured at transducer (kPa)</td>
</tr>
<tr>
<td>Pbm</td>
<td>system of problem entities</td>
</tr>
<tr>
<td>Pr</td>
<td>set of product entities</td>
</tr>
<tr>
<td>Q</td>
<td>volumetric flow rate (m³/hr)</td>
</tr>
<tr>
<td>R</td>
<td>bubble radius at any height (in chapter 4)</td>
</tr>
<tr>
<td>R</td>
<td>ideal gas constant (J/K mol) (in Eq. 6.6)</td>
</tr>
<tr>
<td>R₀</td>
<td>internal radius of annular die</td>
</tr>
<tr>
<td>R_L</td>
<td>final bubble internal radius</td>
</tr>
<tr>
<td>Rs</td>
<td>set of resources</td>
</tr>
<tr>
<td>S</td>
<td>total system</td>
</tr>
<tr>
<td>S_Ln</td>
<td>system of solution entities</td>
</tr>
<tr>
<td>S^x</td>
<td>system at x position in sequence of systems</td>
</tr>
<tr>
<td>S_N</td>
<td>system of natural processes</td>
</tr>
<tr>
<td>S_H</td>
<td>system of human processes</td>
</tr>
<tr>
<td>S_E</td>
<td>system of economic processes</td>
</tr>
<tr>
<td>S_y^x</td>
<td>system of y processes at x position in sequence of systems</td>
</tr>
<tr>
<td>T</td>
<td>temperature (K)</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>Tr</td>
<td>set of processes (from transformation)</td>
</tr>
<tr>
<td>v_1, v_2, v_3</td>
<td>velocity in machine, transverse and thickness directions</td>
</tr>
<tr>
<td>W</td>
<td>width of slit (m)</td>
</tr>
<tr>
<td>z</td>
<td>axis of flow along length of slit or machine direction</td>
</tr>
<tr>
<td>(\dot{\gamma}_a)</td>
<td>apparent shear rate (s⁻¹)</td>
</tr>
<tr>
<td>(\dot{\gamma}_w)</td>
<td>shear rate at wall (s⁻¹)</td>
</tr>
<tr>
<td>Δp</td>
<td>pressure across the bubble (kPa)</td>
</tr>
<tr>
<td>ΔRU</td>
<td>change in resource utility</td>
</tr>
<tr>
<td>ξ_1, ξ_2, ξ_3</td>
<td>machine direction, transverse direction and thickness directions</td>
</tr>
<tr>
<td>η</td>
<td>predicted viscosity (Pa.s)</td>
</tr>
<tr>
<td>η_t</td>
<td>true viscosity (Pa.s)</td>
</tr>
<tr>
<td>θ</td>
<td>angle between axis of bubble and tangent to bubble surface</td>
</tr>
<tr>
<td>(\sigma_{11}, \sigma_{22}, \sigma_{33})</td>
<td>stress in the machine, transverse and thickness directions (Pa)</td>
</tr>
<tr>
<td>(\tau_w)</td>
<td>shear stress at wall (Pa)</td>
</tr>
</tbody>
</table>
1. Introduction

Humans organise themselves and their surroundings by making decisions about what to incorporate, if and how to change it, and what to discard by differentiating the value of various entities. The number and diversity of entities continually increases due to a proficient industrial economy that extracts, transforms, produces, markets, sells and discards incessantly. There are, however, limits constraining these activities which affect how sustainable industrial economic processes are.

Technologies designed to respond to these limits and promote more sustainable practices have emerged. In fact, they have emerged to such an extent that many financial markets around the world now report on something that has been called a ‘cleantech index’. That index includes businesses that operate in renewable energy, alternative fuels, waste and recycling, energy efficiency and carbon sectors [1, 2]. Table 1.1 provides some figures for ASX listed cleantech companies for the calendar years (CY) of 2011 and 2013.

Table 1.1: Figures for the Australian cleantech sector and comparisons with ASX listed companies for calendar years (CY) 2011 and 2013 [1, 2].

<table>
<thead>
<tr>
<th></th>
<th>Cleantech sector (CY11)</th>
<th>ASX total (CY11)</th>
<th>Cleantech sector / ASX total (%) (CY11)</th>
<th>Cleantech sector (CY13)</th>
<th>ASX total (CY13)</th>
<th>Cleantech sector / ASX total (%) (CY13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of companies</td>
<td>84</td>
<td>84</td>
<td></td>
<td>84</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>Revenue ($bn)</td>
<td>15.5</td>
<td>19.0</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Market cap. ($bn)</td>
<td>9.2</td>
<td>15.3</td>
<td>1336</td>
<td>1527</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>New equity ($bn)</td>
<td>0.26</td>
<td>2.78</td>
<td>42.31</td>
<td>52.53</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>New equity / Market cap. (%)</td>
<td>2.8</td>
<td>18.2</td>
<td>3.2</td>
<td>3.4</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

Although the number of listed cleantech companies didn’t change, there were increases in revenue (18.4%), market capitalisation (66.3%) and new equity (969%) between 2011 and 2013. According to Table 1.1, the sector percentage of market capitalisation of the total ASX also rose slightly. Without the benefit of analysing underlying data, these figures on
appearance suggest that there was some growth of support for cleantech technologies within that timeframe.

With respect to sustainable development, an interesting question arises: is such growth, as indicated by one country’s cleantech sector, in any way indicative of what is sufficient to develop a sustainable industrial economy? As industrial economic processes impinge progressively upon biospheric systems, are adaption and problem mitigation techniques likely to be effective? Note that Table 1.1 shows market capitalisation for the cleantech sector is only 1.0% of the total ASX. And if it is not sufficient, what sort of indicators, methods or tools would benefit such an assessment?

Compare this readily available economic data with some readily available physical data. The recent IPCC report [3] provides a figure (with high confidence) of 9.5 ± 0.8 GtC/yr for carbon dioxide emissions due to fossil fuel and cement production in 2011, a 54% increase on the 1990 level. Atmospheric concentrations of the greenhouse gases carbon dioxide, methane and nitrous oxide have increased by about 40%, 150% and 20% compared to pre-industrial levels, respectively. The same report [3] also includes these statements:

‘Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes... It is extremely likely (95-100%) that human influence has been the dominant cause of the observed warming since the mid-20th century.’

‘Continued emissions will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.’

At face value, it would appear that apparent solutions (as measured by the ASX economic data [1, 2]) lag apparent problems (as measured by the IPCC physical data [3]) and considerably more support for sustainable industrial economic practices is required to avoid problem growth.

1The ASX cleantech sector data is used as a convenient aggregate indicator of sustainable industry support in the absence of analyses of the sustainable practices of individual company operations, whether they are part of the cleantech sector or not.
Independent of opinions regarding what level of urgency these data may indicate the case remains that the rate of solution implementation within a system must surpass the rate of problem proliferation within that system if the system is to be sustained. Ideally, managing a system thus entails thorough knowledge of the system to understand its problems and to make well-informed decisions with respect to possible solutions. The complexity of the interaction between the industrial economy and natural ecosystems, however, significantly impedes any common comprehension of the dynamics involved and confuses decision making processes regarding long term sustainable development. The situation at hand requires means to obtain greater certainty of information, clarity of knowledge and consensus of opinion if it is to improve. It is the overarching aim of this work to investigate possibilities for establishing such means.

To begin with, the many meanings of abstract data and the influences of parts per million of invisible greenhouse gases are not as tangible to the general population as the aesthetics, hazards and health risks of litter, debris and accumulating waste [4-6] when it comes to understanding the environment/human activity interaction. Accepting this view, the problem of material waste accumulation is used here as a vehicle to approach broader issues of sustainable development and to elicit possibilities of how those broader issues may be resolved. Essentially, this focus on material waste is adopted as a strategy to grasp the system complexity involved in the present discussion. From a dynamic perspective, the accumulation of material waste represents a stagnation of material flow within a materially dependant system. That is, a system that does not exist without the inclusion of matter. Waste must be removed or transformed to a benign form to maintain the system’s function. It is from this perspective of material flow that the research proceeds.

The hypothesis to pursue, then, is that knowledge of the influences and consequences of material flow and transformation can be used to understand the interaction between the industrial economy and natural ecosystems. If the hypothesis has merit, it will be possible to use that understanding to construct tools suitable for assessing and developing sustainable systems. The following section outlines the content and structure of argument chosen to pursue this thesis.
1.1 Choosing the content and structure for the research

Figure 1.1 illustrates the structure and content of the system of inquiry chosen for the research. It may prove useful, however, to first provide a brief chronology of when the parts came to be and why they are included here. The experimental work presented in chapters 4, 5, and 6 was performed in the mid 1990s just as research into biodegradable plastics was attracting significant attention. Development of a new product invites scrutiny of its economics and it was while researching these product aspects that the opportunity to start a material reuse business arose. This experience provides the subject matter for the case study presented in chapter 9. Starting a business operation focused on a city’s commercial and industrial solid waste is a useful contrast to addressing plastic waste in the laboratory. While the former’s primary focus is profitability, the latter’s focus is knowledge. While one is on the scale of a society, the other occurs in the laboratory. But they are both focused on the encompassing issue of avoiding material waste accumulation. It was when reflecting upon the work of the laboratory and the business model that it occurred to integrate the material waste experiences of the two different instances. This process has been rendered as the conceptual model of a sustainable system presented in chapter 7, and then demonstrated in chapters 8 and 9.

In light of the material waste experiences, the position is taken in the present discussion that a shift to a sustainable industrial economic system is too slow. That is, the rate of implementing solutions is less than the rate at which problems arise, in spite of technologies existing to promote the contrary. Therefore, rather than a representative science/engineering research dissertation, the liberty of the less orthodox path just described is taken to unearth possible alternative investigative methods.

Enveloping the entire content in Figure 1.1 is the question of how to resolve sustainability issues in appropriate time. This is simply a corollary of the comparison of rates at which problems and solutions manifest mentioned above. That question undergirds the whole of the work despite any immediate discussion. The material waste accumulation problem provides the focus for the research and ties together the main body of six chapters as well as the examples provided in the two appendices. The more novel aspect of the structure is that it contains within it an entire stand-alone laboratory research study, a business case study and a conceptual model construction, collectively presenting diverse methods to develop material waste solutions. Content of each of the chapters is outlined below.
Figure 1.1: Structure and content for research into the resolution of material waste and sustainable development issues.
1.1.1 Chapters 2 and 3: Literature regarding sustainability and for modelling a sustainable system

The successes and challenges associated with sustainable development and establishing a sustainable industrial economy are overviewed in chapter 2. The literature that exists pertaining to sustainable development is very extensive and so an overview of the variety of material relevant to industrial processes is provided. Since sustainability is a multi-disciplinary pursuit it also contains information about generally applicable concepts as well. It is divided roughly into six sections: definitions and principles (e.g. physical and conceptual references, strong and weak positions); measurements, indicators and other assessment tools (e.g. LCA, EF); decision-making (e.g. multi-criteria decision analysis, software tools); implementation; describing a sustainable system; and summary comments.

Chapter 3 sets out to provide background information relevant for constructing a response to the findings of chapter 2. The first part equips the reader with a better awareness of the author’s perspective on the problem with sustainability issues, where complexity is a central theme. As the complexity of a system increases with time, so does the complexity of its problem solving systems, which has significant implications for a society’s ability to sustain itself [4]. It is important to understand the resilience and stability of systems and how the human gift for abstracting knowledge from the environment is the key to resolving complex issues.

The second part presents the issue of material waste accumulation directly and relates its consequences for a sustainable system to thermodynamic and resource utility considerations. The third part provides a background for the laboratory study presented in chapters 4, 5 and 6. Plastics are chosen as an example of a material entwined with the functions of modern society. The flow of plastics in the economy and their impact as a waste product is outlined. Plastic packaging in particular is highlighted. Finally the subject of the experimental study, a starch-based biodegradable packaging film is introduced.

1.1.2 Chapters 4, 5 and 6: Starch-based biodegradable plastic packaging film experiments

Chapters 4-6 present an experimental study conducted as a technological response to plastic waste concerns. It is a previously unpublished study into the development of a
biodegradable starch-based plastic packaging film from a chemical engineering, plastics processing perspective. Referring to Figure 1.1, chapter 4 provides a review of literature for a relevant experimental design, which is described in chapter 5. This includes knowledge regarding plastics processing, particularly blown film extrusion, starch properties and processing, and rheological modelling. The results of extrusion trials, material property analyses and viscosity modelling are presented and discussed in chapter 6.

As part of this thesis, the experimental study is not so much used to present a piece of innovation, but to provide an example of the common method of using scientific analysis to investigate a technical solution. In this case, the rheological analysis also contributes the fundamental concepts of material flow and transformation adopted to describe the conceptual model described later in chapter 7.

1.1.3 Chapter 7: Conceptual model of a sustainable system
The experimental study provides the practical experience of material flow for contributing concepts to a model of a sustainable system in chapter 7. The model forms the centrepiece of the dissertation and aims to provide a tool for assessing and developing sustainable systems by way of organising information. The shadow beneath the chapter 7 box in Figure 1.1 denotes it is a theoretical exercise in looking at the material waste problem, on a different plane to the practical ones of chapters 4-6, 8 and 9. Generally, the purpose of constructing a model of a system is to facilitate comprehension of its qualities efficiently to a broad population, and that is precisely its purpose here. It references the laboratory work in context of the material in chapter 3, and can be regarded as a meta-study, or study of a study. It presents a fundamental way of examining material waste and sustainability issues in general with a view to expediting them. In contrast to the experimental study, it is a method of problem solving pursued through a ‘synthesis of facts and theories’ [5] rather than an analysis of parts. The experiments and model combined present a complementation of analysis and synthesis, a technique that will prove to become increasingly important for addressing sustainability issues. It will be seen that the model addresses issues such as integration of systems, the representation of time in analysis and analysis adaptability that are review in chapters 2 and 3.
1.1.4 Chapters 8 and 9: Model demonstrations

To demonstrate how the model presented in chapter 7 can be applied, it is used to reinterpret parts of the biodegradable plastics study of chapters 4-6. The process of producing the viscosity models and the process of producing a plastic packaging film are used as scenarios to illustrate how the same fundamental concepts of the model are applicable in diverse circumstances. These demonstrations are an important part of the work since theoretical strategies that claim to address material waste and sustainability issues must also be practical [6]. Both the problem scenario of plastic waste produced by petrochemical based polymers and the potential solution scenario of biodegradable starch based polymers are also compared using the model concepts to show the types of analytical components that are involved.

The other vehicle for explaining and demonstrating the model is an existing material reuse business that illustrates a commercial approach to material waste and resource conservation solutions. In that instance, the model principles are used to design a rudimentary information system. It analyses processes of the warehouse operation and highlights data to gather and process that is pertinent for improving the overall efficiency of the business. In other words, the goal of the information system is to increase the business’ chances of sustainability.

In both of these examples, the analysis is primarily qualitative. However, a generic process to be pursued to obtain quantitative results is provided in chapter 7. The points at which this is applied to the case studies in chapters 8 and 9 are included in the respective discussions.

1.2 Summary of the research objective

The position is taken that problems curtailing sustainable development are increasing at a rate greater than potential solutions can be implemented. Yet it is unknown by how much, or what the actual limits involved are. Many of the operations prevalent within the industrial economy contribute to this scenario. Making decisions to change it requires significant improvement in information, knowledge and consensus regarding the nature of the problems and paths to solutions, improvement that is impeded by the complexity of how industrial economic systems interact with ecosystems.
It is hypothesised that a focus on material flow and transformation can provide an avenue for coming to terms with the complexity of the economic/ecological systems of interaction; allow a means to re-conceptualise the systems into a simpler, more malleable format; and finally yield tools for assessing and developing sustainable systems. Analysis conducted during the development of a starch based biodegradable plastic packaging film provides the material flow and transformation knowledge that contributes the concepts for synthesising a conceptual model of a sustainable system. The model is explained further and its attributes tested by re-interpreting parts of the laboratory study and also by applying it to a commercial material reuse warehouse operation to develop a rudimentary information system.
2. **Review of sustainability literature**

This chapter presents a review of concepts and techniques important amongst the sustainability literature. It will be used as a backdrop to establish the relevance and value of the model proposed of a sustainable system in chapter 7. Literature that contributes more directly to the construction of that model is presented in chapter 3.

Rectifying an undesirable situation and solving problems is the domain of living systems and a common problem-solving technique employed by a living system can be described by a feedback control loop. In that case, the state of the system is measured against a reference state or set point (chemical gradient or desired temperature, for example) and depending on the assessment of those measurements against prescribed criteria, an action is implemented. The consequences of that action are assessed following measurements of the new state of the system against the reference state, and a new action is decided upon that yields further consequences, and so on until ideally the problem is solved.

Since an objective of the thesis is to investigate the relative rates of problem and solution change within a system, the steps of the feedback control loop used to solve problems described above, are used as the main section headings of the current chapter. The initial aim of this approach is to see how each discrete step of a typical problem solving process is represented in sustainability literature. Sections 2.1-2.4 each comprise a step and section 2.5, representing the move to the next iteration, reviews the process as a whole and highlights what can assist in describing the sustainable system of the thesis title. As such, the content of this chapter is organised as follows:

- Definitions and principles (defining a reference, set point, criteria);
- Measurements and assessments (comparing a system’s position vis-à-vis its reference);
- Decision-making (describing actions for the system to take);
- Implementation (executing the actions decided upon); and,
- Describing a sustainable system (next iteration in the process of solving the system’s problem).
The chapter is summarised in section 2.6. There are sub-divisions within sections for major points of discourse encountered in the literature that are relevant to describing a sustainable industry economy.

2.1 Definitions and principles

‘Sustainability’ and ‘sustainable development’ are often used interchangeably in the literature and that is the case also here. However, for technical completeness, it is worth noting the difference. The noun, sustainability, refers to the ability of an entity or system to be ‘sustained’, the verb. It is a measure of how the entity or system maintains it identity and viability over time. The adjective, ‘sustainable’ in sustainable development then denotes a type of development that can be maintained over time with ‘development’ generally used in the context of human society.

2.1.1 Our common future

It is sustainability of the global community cultivated through sustainable development that the WCED report, ‘Our Common Future’ refers to on pg 46:

‘In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations.’

Within its twelve chapters the report describes sustainable development in several different ways [7]. But the most encountered definition on pg 43 is:

‘Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.’

It provides the most common reference point for beginning modern discussions about sustainability [8-10], suggesting the title of ‘Our Common Future’ was an appropriate one for the authors to choose. From this perspective, the report is a success. However, it is often argued terms like ‘sustainable’, ‘development’ and ‘needs’ are value words, and therefore subjective [11]. They can be interpreted for purpose. The concept of sustainability is also comparatively young, complex and abstract and rests on both factual
and ethical considerations [12]. Therefore, it is not surprising to find that there now exists hundreds of published definitions [13, 14].

Diesendorf [7] suggests that, in the context of the second statement quoted above, the ‘needs’ for ecological sustainability are confused with economic wants. However, he goes on to note that the body of the report acknowledges principles such as ‘equity between and within generations, conservation of biodiversity and ecosystems, dealing cautiously with risk and uncertainty, economic development and well-being, and community participation’. ‘Our Common Future’ [15] will continue to inspire definitions as alternative interpretations are put into practice for different purposes [16]. But the principles that appeal to the construction of sustainability concepts and analytical frameworks are likely to remain the same.

2.1.2 Physical foundations

One of the earliest and clearest proclamations of sustainability principles to guide an industrial society is that by The Natural Step organization. The Natural Step principles for a sustainable society, forwarded by Dr Karl-Henrik Robèrt shortly after the publication of ‘Our Common Future’ [15], have enabled the organization to be considerably influential during its time. Coming from an ecological perspective, The Natural Step prudently includes a dimension of quantification to the definition of a sustainable society by referring to changes in material concentrations [17]:

‘In order for a society to be sustainable, nature’s functions and diversity are not systematically:

I. ...subject to increasing concentrations of substances extracted from the lithosphere;
II. ...subject to increasing concentrations of substances produced by society;
III. ...impoverished by over-harvesting or other forms of ecosystem manipulation.

Together, the three first principles give a framework for ecological sustainability. It implies a set of restrictions within which the sustainable societal activities must be incorporated. Based on that reasoning, a first order principle for the society’s internal turnover of resources is formulated – the fourth principle:
IV. ...resources are used fairly and efficiently in order to meet basic human needs worldwide.'

Working with these principles, The Natural Step has created a systemic approach to strategic thinking for long-term solutions, and has become a global network operating in 13 countries [18]. The importance of an operational definition of sustainability built upon the physical is emphasised by Hannon et al. [19] and Ruth [20] who use the idea of a ‘climax ecosystem’ as a reference system for their definition of sustainability. Using an ecosystem proven to be sustainable for many hundreds of years, they calculate its rate of entropy production and compare it to the rate of entropy production for a human system. If the entropy rate of the human system exceeds that of the reference system, then the human system is not sustainable.

2.1.3 Environmental, social and economic sustainability

Despite the advantages that a physically based definition may provide, particularly for constructing tangible metrics, it may not be pragmatic in many cases. Calculating the rate of entropy change over processes certainly becomes more difficult as the scale of systems decreases and their diversity increases. An approach to sustainability that has proven pragmatic is The Triple Bottom Line (TBL), introduced by John Elkington [21, 22]. An alternative name for the concept is the ‘three pillars’ [23]. By either name, it promotes the balance of economic prosperity, environmental quality and social justice as a means for industry to engage with principles of sustainability. A study by Carew and Mitchell [12] found that responses to questions specifically about one of either environmental, social or economic sustainability were more likely to describe specific actions for sustainability, rather than the very broad terms used to asked to describe sustainability in general.

The TBL or three pillars framework is mentioned often not only in academic literature, but in the corporate and industrial sphere as well, in the form of business principles for example, on account of it proving particularly accessible for the work of engineers [12]. The Institution of Chemical Engineers (IChemE) adopts the TBL approach explicitly in its sustainability metrics guidelines document [24]:

‘The impact of industry on sustainability can be summarised in the “triple bottom line”, covering the three components - environmental responsibility, economic return (wealth creation), and social development.’
TBL is also apparent in the definition the Organisation for Economic Co-operation (OECD) adopted from the US Department of Commerce’s (USDOC) Sustainable Manufacturing Initiative [25] for sustainable manufacturing. It applies at the process or product level and defines sustainable manufacturing as:

‘the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound.’

Statements using the three pillars to capture sustainability within an organization’s operations are common practice. Gagnon et al. [26] reviewed lists of sustainability principles from both general and engineering-focused sources. From these, they generated a set of fifteen principles for sustainability in general and another fifteen for sustainable engineering. They used a triangle with each of the points labeled one of environment, society or economy and arranged the fifteen principles about the triangle to represent how they relate to each other. This exercise illustrates the extensive acceptance of three pillar frameworks and how complex and abstract notions such as sustainability can be compartmentalised to improve operability.

Picturing sustainability as the co-existence of parts, like economy, environment and society, brings forth questions of how practical a division is, how many divisions should there be, and how equally important they all are. For example, the five capitals model [27], which divides available capital into human, social, built, natural and economic capital, defines sustainability as depending on the maintenance or increase of the stock of a particular capital at the expense of other capitals. If consumption declines capital stock, it is not sustainable. It is at this point of declaring preferences for how resources are managed that the different schools of thought regarding what sustainability is become more apparent.

2.1.4 Strong and weak sustainability

The detail of definition is mainly a practical matter [11]. But opinions about the value of and distribution between the various capitals lead to what is referred to as the weak and strong sustainability paradigms [28], generally aligned with neoclassical and ecological economics [29-31]. Weak sustainability allows man-made capital substitution of natural
capital to a high degree, whereas the strong position is that fundamental services provided by nature cannot be replaced by man-made capital [29]. Neumayer [32] refers to them as the ‘substitutability’ and ‘non-substitutability’ paradigms respectively, alluding to the fundamental influence that personal choice of capital has on how sustainability is defined. One set of definitions of sustainable development emphasise the role of the environment as a supplier of resources for current and future economic processes while other definitions stress the integrity of the resource base [20].

Ayres [29] provides a physical analysis of the debate concluding that while there is considerable scope for substitution, the limits to replacing natural capital are real and important considerations in the medium term. Meadows [11] notes it makes no sense to assume total substitutability of one form of capital for another, nor to assume no substitutability at all. An ecological economics perspective, while leaning towards the latter of these positions for example, would emphasise the finiteness of both resource input (‘source’) and of the waste and pollution assimilation capacity of the environment (‘sink’) [32] and seek to value entities of the industrial economy accordingly.

2.1.5 Defining definitions and principles

Questions such as, ‘What should be sustained?’; ‘What is sustainable?’ and ‘What type of development is sustainable?’ will continue to form the foundation of meaningful definitions and principles that [10, 11]. Or, from an alternative but equally fundamental perspective, identifying what is unsustainable may be easier and prove more practical [28].

The idea of a ‘top-down’ approach for formulating criteria based on these questions is appealing. A state to which society aspires can be described and then the criteria required to achieve that state can be described [23]. This method has been referred to as ‘backcasting’ and can facilitate a systematic approach to handling complex problems especially when the solvers of the problem themselves are part of the system [33], which is certainly the case with issues of sustainable development. Such a process may help clarify exactly what entity or system is unsustainable by its absence from the future vision.

If is often inferred throughout the literature that the multiplicity of sustainability interpretations is a negative influence on moving towards a sustainable industrial economy. However, Carew and Mitchell [12] present a refreshing case for accepting this scenario for what it is and taking advantage of the diversity that exists:
‘Being partly value-based and focused on complex systems means that the conceptual contest about sustainability is both inevitable and healthy, and offers a means to give voice to different stakeholder perspectives, to further evolve the concept, and supports the continuing flexible application of sustainability in contextualised consultative decision-making.’

Undoubtedly, definitions and principles will continue to emerge. The concepts for sustainability and sustainable development will be applied in a greater extent to more economic sectors and as a greater number of the global community become engaged with sustainable conduct. But this is only the initial stage of resolving the issue. For a conscious shift towards a sustainable system of industry, being able to measure and assess progress is imperative.

2.2 Measurements and assessments

The Earth Summit in Rio de Janeiro in 1992 provided motivation for the next key step in the control loop in a similar way the WCED did for definitions in 1987. It explicitly stated the need to develop means to measure sustainability, that is, to develop indicators and metrics:

‘Indicators of sustainable development need to be developed to provide solid bases for decision making at all levels and to contribute to the self-regulating sustainability of integrated environment and development systems.’ [34]

The diverse interpretations of sustainability have in turn seen the development of indicators for its measurement become an industry unto itself, as the need to adapt concepts of sustainability to real situations continues to grow.

2.2.1 Sustainability indicators

In terms of providing support for sound business strategy, Schwarz et al. [35] suggest indicators should satisfy the following criteria:

- Simple – not requiring large amounts of time or manpower to develop
- Useful to management decision-making and relevant to business
• Understandable to a variety of audiences, from people in operations to finance to strategic planning  
• Cost-effective in terms of data collection  
• Reproducible – incorporating decision rules that produce consistent and comparable results  
• Robust and non-perverse – indicating progress toward sustainability when improvement has in fact been made  
• Stackable along the supply chain so they are useable beyond the particular fenceline for which the calculation was performed  
• Protective of proprietary information – preventing the back-calculation of confidential information.

A prominent example, the Ecological Footprint (EF), displays a number of these characteristics. It has been successful because it captures many ideas using a single number with units and a name that have strong intuitive and metaphorical appeal. It measures the environmental impact of an entity (e.g. a person, city, industry, etc.) by the amount of land that entity requires for its maintenance [17]. It provides ‘a yardstick for measuring the ecological bottom-line of the renewable use of the biosphere – a precondition for securing people’s quality of life’ [17]. However, its calculation can be oversimplified; it doesn’t account for marine resources or the differences in biocapacity across landscapes; substances for which it is difficult or impossible to estimate an assimilation capacity can’t be considered (e.g. synthetic materials); and it needs to become dynamic to reflect implications of future footprints [11, 17]. Any weaknesses perceived in an individual indicator, however, are simply an opportunity for the scope and development of alternatives.

The Global Reporting Initiative (GRI) guidelines for sustainability reporting [36] seeks a practical compromise between too many indicators and enough indicators to be broadly applicable. Suitable for companies, councils, governments etc, the guidelines with a selection of 92 indicators (divided into 9 economic, 34 environmental and 48 social indicators) in the most recent version [36], represent a promising enterprise in terms of information management and supplying a common vision. Table 2.1 shows how the aspects are divided amongst the categories with the number of individual indicators shown in brackets.
Table 2.1: Categories, aspects and number of indicators (shown in brackets) included in the latest GRI guidelines [36].

<table>
<thead>
<tr>
<th>Category</th>
<th>Economic (9)</th>
<th>Environment (34)</th>
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<tbody>
<tr>
<td></td>
<td>Economic performance (4)</td>
<td>Materials (2)</td>
</tr>
<tr>
<td></td>
<td>Market presence (2)</td>
<td>Energy (5)</td>
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<td></td>
<td>Indirect economic impacts (2)</td>
<td>Water (3)</td>
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<tr>
<td></td>
<td>Procurement practices (1)</td>
<td>Biodiversity (4)</td>
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<tr>
<td></td>
<td></td>
<td>Emissions (7)</td>
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<td>Effluents and waste (5)</td>
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<td>Products and services (2)</td>
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<td>Compliance (1)</td>
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<td>Overall (1)</td>
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<td></td>
<td>Supplier environmental assessment (2)</td>
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<td></td>
<td></td>
<td>Environmental grievance mechanisms (1)</td>
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Aspects

<table>
<thead>
<tr>
<th>Category</th>
<th>Social (48)</th>
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<tbody>
<tr>
<td></td>
<td>Labour practices and decent work (16)</td>
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<tr>
<td>Sub-cATEGORIES</td>
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<td></td>
<td>Employment (3)</td>
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<td></td>
<td>Labour management relations (1)</td>
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<td></td>
<td>Occupational health and safety (4)</td>
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<td>Training and education (3)</td>
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<td>Diversity and equal opportunity (1)</td>
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<td></td>
<td>Equal remuneration for women and men (1)</td>
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<td></td>
<td>Supplier assessment for labour practices (2)</td>
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<td></td>
<td>Labour practices grievance mechanisms (1)</td>
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Benefits of centrally organised systems like the GRI sustainability reporting initiative include improved understanding of abstract issues, international access to data that is working towards a standard practice, and possibilities for future data integration [36]. However, using the framework is not mandatory and those applying such a reporting system have considerable discretion as to what they choose to disclose, which will tend to undermine the ideal potential of the GRI and similar systems [30].

The number and diversity of indicators in the literature is extensive and knowing what to use when is not necessarily an obvious task. Rivera et al. [37] quote an International Institute for Sustainable Development (IISD) report from 2013 that states 895 initiatives exist worldwide to develop sustainability indicators for application to cities to global projects. They then describe a technique for identifying, tracking and reporting
sustainability indicators for a region through text data mining of local news media to save time and resources spent choosing from all those available. But the method had problems with identifying and geo-referencing some of the more serious problems within a region that were not necessarily news worthy. Also, Lee et al. [14], realising the difficulty of finding a relevant indicator for manufacturing companies to assess their own sustainability, proposed a framework for a research inventory to make using available indicator resources more efficient.

Further attempts to categorise the body of indicator literature include a review by Singh et al. [38]. They provide notes on a broad collection of general indices under twelve classifications including innovation, knowledge and technology, development and variations on ecological, social and economic and integrated indices. An alternative method of understanding the breadth of indicators, is the framework forwarded by Ness et al. [9]. It is useful for seeing how the different types of indices relate to each other according to their outlook (retrospective versus prospective) and their application, rather than assigning them simply to one category or another.

Sustainability metrics and indicators for process and manufacturing industries are plentiful, with an author of an indicator often emphasising a particular scale of application or particular aspect of the three pillars to address an outstanding need. Historically, sustainability indicators for industrial processes have built upon physical quantities such as material and energy intensity, water consumption, toxic and pollutant emissions, solid waste and land use [39]. Indicators that explicitly address social dimensions in industry are far fewer, but appreciation of their importance is increasing. Husgafvel et al. [40] provide a focus on social metrics for plant-level sustainability, recognizing the fact that social sustainability is often overlooked in assessments of industry, despite it being highly relevant in the context of informed decision-making. A reason for this appears to be a lack of analytical and theoretical foundation from which to construct indicators with a social focus [41]. However, Kloepffer [42] notes a recent and rapid increase in publications pertaining to societal life cycle assessment (SLCA).

Other variations of measurement or assessment techniques for industry include a rapid assessment for SMEs using a questionnaire of 133 questions [43] and a company level probabilistic method in the strong context with dynamic evaluation [30]. The latter publication is one of the few that explicitly consider time as integral to the indicator, as
does Shepon et al. [44] quite explicitly with EcoTime, an indicator with wide application that equates the environmental burden of a process or product in time units. Using time units satisfies the requirement of an indicator to be communicable to a wide audience, a problem that restricts the utility of many existing indicators. Shepon et al. [44] suggest the attractive idea of being able to label common day items with their EcoTime. For example, food items can be labeled to reflect their environmental impact in a similar manner to how nutrition information is provided. Access to the kind of detailed data that would facilitate this, which is often proprietary, is not as straightforward as obtaining nutritional information, which is far more generically available.

Given the volume of work devoted to constructing sustainability indicators, it is necessary to question their value. Do predominant global SDI metrics convey a consistent message towards sustainable development? Wilson et al. [45] find that different metrics applied at the national level yield varying interpretations of a nation’s sustainability. This implies that a clear direction towards sustainable development at the global level is lacking. Böhringer and Jochem [46] conclude rather abruptly that many indices applied in national policy practices fail to fulfill fundamental scientific requirements making them rather useless if not misleading with respect to policy advice. There are too many indices when what policy makers tend to demand is a single aggregate index.

It was said in 2002 that the ‘... largest gaps in current indicator work probably consist of the practical challenges that still need to be met and solved... data collection and quality assurance are among the largest challenges that indicator developers face’ [47]. Access to data and the assurance of its quality still remains a key impediment to not only establishing reliable indicators, but to all forms of measurement and assessment of sustainability. Given the requirement of private entities to protect their own information as part of maintaining their own viability, it is difficult to see exactly how to move forward in this respect.

### 2.2.2 Life cycle assessment (LCA)

Also, referred to as life cycle analysis, LCA is a methodological tool used to quantitatively analyze the ecological impact of products in four distinct phases [48-50]:

- Goal and scope definition
- Life cycle inventory (LCI)
Life cycle impact assessment (LCIA)

It provides the most suitable means for product comparisons and strategic decision making in light of systemic inputs and outputs from the ‘cradle-to-grave’ [42, 51, 52]. However, LCAs are time-consuming and complex. Also, an LCA might be regarded as providing a framework for collating and organising the information associated with a product but it stops short of providing indicators as such, since it aims to be broadly applicable and open to interpretation by the analyst. This can lead to results that are difficult to communicate broadly.

The Eco-indicator 95 [51] and its extension, Eco-indicator 99 [53], are amongst the most widely used environmental performance assessment tools based upon the impact data gathered through LCA [54]. Eco-indicator 95 [51] creates indicators for LCA by expanding LCA to include a weighting step. As such, non-comparable units noted by Ayres in 1995 [55] are, to a practical extent, addressed by Eco-indicator 95 through the weighting methods introduced there. The issue of weighting in the LCIA is itself subject to many methods since there is no generally accepted procedure for normalisation and weighting. Applying statistical analysis performed on survey responses is one technique suggested for deriving weighting measures. Itsubo et al. [56] used the statistically significant results of a survey to develop integration factors to apply in LCA case studies. They pose a problem since they aim at the comparability of variables even though these are obviously not comparable [46].

By coupling LCA with the criteria above, data gathered by LCA gains its value as part of other indicator and assessment systems [41]. Shuaib et al. [57] forwarded a Product Sustainability Assessment (PSA) that included the 6Rs (reduce, reuse, recycle, recover, redesign and remanufacture) and TBL over four life cycle stages (pre-manufacturing, manufacturing, use and post-use) and called it ProdSI. Mani et al. [50] used LCA to assess the sustainability of manufacturing processes using only the environmental impacts, with social and economic ones being outside the scope of the work. The fact that it is only environmental impacts that are considered makes the claim to a sustainability assessment disputable. The lack of consideration of social factors is noted by Yi et al. [58] as impeding good decision-making practices in the MSW assessment examples of LCIA they present.
A major shortcoming of LCA, just as in many instances of indicator descriptions, is access to enough quality data of the right kind [55]. An early critique by Ayres [55] noted the use of data that can’t be checked, either by lack of referencing or by confidentiality, as a major problem. More recently, data quality was noted as a continuing issue [59]. As an example, the complexity of the problem often prevents the availability of knowledge relevant for supporting uncertainty analysis within assessments. This is not helped by subjective choices related to using secondary data [60]. Many studies attempt to provide some guidance about uncertainty on specific data, but none provides a complete picture of the issue [59].

Working with imperfect knowledge is a well known and persistent issue, but LCA still has substantial value even though it tends to expose tradeoffs rather than an unambiguous ‘best’ choice. Since there is no definitive method regarding assumptions and defining system boundaries, it is wiser to employ a number of LCIA methods to make decision-making processes more robust [49, 61]. Another recommendation is to explicitly justify the methods of LCIA selected to assist the reader as much as possible in understanding limitations of any results [61].

One thing to bear in mind, though, is that conducting an LCA is not necessarily a positive achievement. It is possible that LCA can be considered to have little or even negative value if the underlying physical data for such entities as critical pollutants is wrong [55].

2.2.3 Assessing sustainability
Compared to LCAs that focus on the environmental impacts of a product, assessing how sustainable a product is requires the incorporation of social and economic aspect. In turn, it means the analysis can move away from the product focus of LCA and provide tools for application to policies, plans, programmes, projects, pieces of legislation and processes in general [23].

While it may be useful to have specific indicators at the smaller scales, the variety of them poses a huge problem at the policy level, since policy makers prefer aggregate indices [46]. In such cases, the broader scope of a sustainability assessment is appealing. Work described as sustainability assessment refers to an integration of disparate indicators. Integration, or aggregation, of indicators is desirable in many cases to facilitate decision-
making by organising them into less, but more manageable indicators. Often the integration refers to considering the three pillars simultaneously to take a more holistic view of system being assessed [62, 63].

Azapagic et al. [64] provide a case study of the design of a vinyl chloride monomer process based on LCA. Sustainability criteria are able to be identified, the sustainability of the processed assessed, and the information made available for improving the design. Heijungs et al. [65] build on the LCA methodology to present a framework with which different models of environmental analyses can be applied, as well as having the ability to include economic and social aspects, hence, as they claim, integrating the three pillars of sustainability. The technique is referred to as life cycle sustainability analysis (LCSA). It involves the modelling of a technological system that contains the life cycle of a product, to which is added environmental, economic and social data of different unit processes within that technological system. Klopffer [42] presents LCSA as the conceptual sum of LCA, life cycle costing (LCC) and societal life cycle assessment (SLCA). It is noted there that the strength of LCA is that quantification is possible and ideally that should carry over to LCC and SLCA. This is not a problem for LCC but remains very challenging for SLCA. Yet, given the significance of the goal, it is important that assessment tools are continually improved to overcome anyd difficulties.

Similarly, Krajnc and Glavic [66] design a model to obtain a composite sustainable development index for a company that combines information pertaining to its economic, environmental and social performance with time. The index is developed with the role of decision-makers in mind. Each of these cases, however, might be considered a conglomeration of parts rather than actual systemic integration.

There are problems inherent in this ‘additive’ approach that can conceal conflicts and decision-making difficulties [67]. As noted by Gibson [63]:

‘Effective integration of the major interdependent considerations in sustainability assessment is likely to be frustrated by the established capacities of experts trained separately in social, economic and ecological fields, by the habitual collection of data separately under these categories, and by the common division of government mandates into separate social, economic and ecological authorities…. ’
'...This makes the three pillars approach a poor fit with intertwined sustainability problems, which by definition do not fit tidily into any one of the three pillars and which demand responses that seek multiple, mutually reinforcing contributions to a positive shift in practice.'

From an alternative perspective, standardisation of indicators may be considered a type of integration, in that the aim is to improve communication for decision-making processes. Standardised sustainability indicators for industry would assist in identifying more sustainable options through [8]:

- comparison of similar products made by different companies;
- comparison of different processes producing the same product;
- benchmarking of units within corporations;
- rating of a company against other companies in the (sub-)sector;
- assessing progress towards sustainable development of a (sub-)sector.

Overall, it is important to understand what processes an assessment for sustainability entails and how its structure lends itself to integrating the diverse components of knowledge that informed decision-making entails. One well-thought out approach advocated by Morrison-Saunders and Pope [68] is that of thinking strategically and posing a strategic level question, rather than proposal-specific thinking. This should genuinely increase the opportunity for conducting properly integrated assessments and translate to more sustainable decision-making and outcomes.

### 2.2.4 Other measurements and assessments

Material-input-per-service (MIPS) also referred to as ‘Material Footprint’ was developed by the Wuppertal Institute in the early 1990s. It is founded on a similar concept to EF but rather than being expressed in units of area, it is presented in units of mass. It is comparable to the input-side of a LCI in typical LCA and is able to take advantage of the extensive LCA databases that now exist. It consequently allows MIPS analysts to extend their customary material input indicators and LCA analysts to extend their own potential indicators using a single set of tools [69].

Both LCA and MIPS have associations with input-output analyses encountered in economics through what has become known as environmentally-extended input-output
(EEIO) analysis. EEIO is a long established technique that provides a simple and rapid method to evaluate the relationship between economic activities and downstream environmental impacts [70]. EEIO can also take advantage of database structures to deliver powerful support for developing environmental and economic policies [71]. Combined with the backcasting technique, a sustainability goal can be defined and various economy wide scenarios can be set up to see which would meet the goal [72].

Sustainability metrics, indicators and assessments provide the information needed to make better decisions, measure progress and monitor feedback systems to ensure development of a system is sustainable. But since there is no consensus on their design or use, it is important for users of these tools to be aware of the philosophies, biases and limitations they entail if the necessary information for making effective decisions is to be conveyed [45, 46].

2.3 Decision-making

‘Our common future’ [15] was written in response to increasing recognition of growing inequalities between rich and poor and degradation of the biospheric systems. In large part these phenomena are symptomatic of critical failures of decision-making processes that don’t account for system interdependencies [73]. Such interdependencies also include reference to the definitions, principles, measurements and assessments originally employed. It stands to reason then that sustainability indicators are increasingly being used for decisions in the context of sustainable development and it is appropriate to define sustainability indicators as decision criteria [74].

The limitations of indicators and the quality of the information they capture will impact directly on the possible quality of decisions ultimately made [47]. The effectiveness of decision-making processes is also tempered by the methods used to handle the often conflicting interests of multiple stakeholders presented with a number of options, or unclear alternatives [74]. The need to consider these multiplicities makes integration a discerning characteristic of sustainability and so the three pillars or TBL approaches used for assessments can make them a limited choice for sustainability problems, despite their practical advantages [63, 73]. A conventional method of decision-making trades-off between ecological, social and economic concerns outside of the assessment, whereas in a sustainability assessment policy and development objectives are considered together to address trade-offs or other decisions directly [63, 73]. A systems approach is required and
decision-makers must take a holistic view in trying to integrate and balance the three pillars criteria over the life cycle of each of the alternatives [74].

Bebbington et al. [75] discusses developments within the accounting discipline designed to support sustainable development decision-making and evaluation. They propose sustainability assessment models as a viable alternative to cost-benefit analysis. It is also possible to leverage the utility of LCA by converting preferences of decision-makers into weights for application in LCA via linear programming [76].

Overall, the decision-making process can be split into three stages [77]:

- Problem structuring;
- Problem analysis; and
- Problem resolution.

Problem structuring involves [74]:

1. Identification and involvement of stakeholders;
2. Definition and understanding of the problem;
3. Identification of key sustainability issues;
4. Identification of decision criteria (sustainability indicators);
5. Identification of alternatives; and

Each of these steps is the subject of significant discussion. In fact, it is here that defining sustainability, choosing how to measure and assess it, (as discussed in sections 2.1 and 2.2), and decision-making processes appear as part of the same process – namely a scheme to develop a system sustainably. The complexity, uncertainty and scale become apparent, and ad-hoc approaches tend to be ineffective meaning decision making tools are required [78].

2.3.1 Multi-criteria decision making (MCDA)
MCDA is a formal technique used to organise and synthesise information towards understanding the problem, identify decision-making criteria and choose the best option based on the importance of those criteria. It aims to improve on informal processes by
including transparency, being explicit, providing an audit trail and being left open to scrutiny by interested parties. Importantly, it also addresses the issue of subjectivity which arises from the value-systems decision-makers hold, and a major cause of conflict [74]. MCDA can be provide design guidelines for materials selection, such as PC housing [79]. In that example, the dimensions are fixed and LCA performed for a number of materials to yield environmental impacts as outlined by the Eco-indicator 99 method. A MCDA method called TOPSIS is used to rank the materials with steel proving to be the most environmentally conscious material and copper being the least.

MCDA in itself is a subject and Azapagic and Perdan [80] provide a tabled summary of numerous MCDA methods. Software applications have been developed for the various approaches to problem analysis, for different types of problems, single or multi-stakeholder arrangements and criteria weighting systems for use with quantitative and qualitative indicators [80].

But it is decision makers making the decisions, not the framework, which at best may only facilitate good decision-making by helping decision-makers better understand the problem and the consequences of their decision for sustainable development.

2.3.2 Decision-making systems for industry

Provided here is a brief description of two systems used in the chemical processing and minerals industries.

The GREENSCOPE (Gauging Reaction Effectiveness for the Environmental Sustainability of Chemistries with a multi-Objective Process Evaluator) methodology is designed specifically for decision-making in the chemical process industry. It uses the ‘four Es’, environment, energy, efficiency and economics to determine whether a particular reaction or process is becoming more or less sustainable [81]. Based upon a ‘gate-to-gate’ life cycle analysis the system has been developed to include a significant array of relevant indicators each associated with best and worst case sustainability values [82].

The aim of any decision-making process is to create a ‘shared understanding of issues, generate a sense of common purpose’ [74]. The implications of complexity, of course, can make this a very onerous task. In the end, making decisions for sustainable outcomes should seek to promote ‘multiple reinforcing gains’ [63, 73], or look for ‘win-win-win’
outcomes for environmental, social and economic agendas, more so than simply striking a balance between the three sets of criteria [68]. It is essential that the decisions finally decided upon do ‘not compromise the fundamental objective of net sustainability gain’ [73].

The SUSOP® framework aims to incorporate sustainable development principles into decisions about the design and operation of resource processing by embedding the following elements [83]:

- An integrated, consistent, project and operation-wide framework for sustainability thinking;
- Initial project definition in sustainability terms, and with an eye to local context;
- Generation of alternatives which incorporate sustainability goals;
- Assessment of alternatives to compare SD impacts on a consistent SD framework basis, supplemented with a decision-support process;
- Involvement of stakeholders in prioritisation of sustainability goals; and
- Life cycle thinking and a focus on system interactions from a holistic perspective.

The framework directly addresses the time restrictions in mining projects, or any project for that matter, tend to lead to a default ‘business as usual approach’ [84]. The framework stresses the need to make a genuine contribution to sustainable mining practices without compromising on financial rigour.

2.4 Implementation

The greater an understanding that the system has of the definition of its sustainability, the greater is the effectiveness of the tools, metrics, indicators applied to the system and, consequently, the effectiveness of its actions can be increased also [17]. From a physical point of view, actions guided by processes that are commonly encountered in a healthy functioning ecosystem contribute to sustainability. The diversity and interdependence of entities, their cooperation and partnership, the cyclic flow of resources and a solar energy base instill flexibility and resilience in an ecosystem that help it to survive disturbances and adapt to changing conditions [85].

As noted in section 2.1.3, redefining sustainability using the three pillars helps conceptualise means of implementation [12]. However, as the scale increases from an individual to a globe, implementing sustainable courses of action understandably becomes
more difficult. It is easy to decide to put a used LDPE plastic container in the recycling bin. But rhetoric at the higher levels has trouble extending to relevant action on the ground as competition between conflicting goals emerges. While the three pillars of economy, ecology and society ‘serve a useful heuristic purpose, the actual interrelations of these three ideals are complex and often contradictory in practice’ [86]. As such, it has been generally difficult to translate theoretical aspirations into practical actions at an operational or factory level [43, 87].

At a processing level, eco-efficiency initiatives, such as reducing material and energy intensity, reducing solid waste, and avoiding breaches of pollutant and toxin emissions, things that contribute directly to both environmental and economic goals, are amongst the most successful. But eco-efficiency measures by themselves do not amount to sustainability [39]. There is a need to also understand sustainable consumption [88]. The importance of implementing sustainability principles early in the design process cannot be underestimated as a means to mitigate potential risks associated with the lifetime of a project [89].

Even in cases where decisions or initiatives exist to promote sustainable development, the decisions may be ‘not binding’ as in the case of many international agreements, or ‘not mandatory’ in the case of reporting. The onus is upon the priorities of the individual person, business or institution to adopt something like the GRI guidelines [36]. To act optimally in the pursuit of sustainability, activity must be reinforced and integrated at different scales through all aspects towards a common understanding of what the goal is [73, 74].

2.5 Describing a sustainable system

Based upon the literature presented in this chapter, this section highlights those ideas and techniques useful for describing a sustainable system in chapter 7. To begin with, it is useful to comment on the structure chosen for discussing the literature. In his introduction to the concept of ‘messes’ when discussing difficult social problems, Ackoff [90] notes:

‘Trial and error require more time than is currently available between changes that require response. The lag between stimulus and response brought about by reliance on experience permits crises to develop to a point at which we are forced to respond to them
with little relevant knowledge. An increasing portion of society’s responses are made out of desperation, not out of deliberation.’

In light of this, the simple control loop used as an example technique of problem solving in this chapter is not appropriate for resolving the complex issues of sustainable development. System complexity is noted often in the literature as a limiting factor on the success of sustainability initiatives [12, 26, 28, 33, 60, 78, 86, 91]. One of the aims in this work then, is to describe a model of a sustainable system that accounts for complex behaviour and allows for an alternative method of problem solving to function within it. Dividing sustainability into environment, society and ecology in the manner of the three pillars has helped dealing with complexity to a degree. The technique has provided a conceptual vehicle that has made significant inroads towards a different way of operating the industrial economy [12]. Economic goals are routinely accompanied by social and environmental goals in the mission statements and slogans of public and private entities alike [26]. However, good intentions are not necessarily sufficient to bring about genuine change. If the latest IPCC report [3] provides any testament as a guide, the ratio of problem generation to solution implementation is currently greater than one.

Therefore, the alternative of defining a sustainable system through physical means [19, 20, 33] appears to be the most prudent to pursue. The theory is that a physical reference state that is common in space and time provides the greatest opportunity for resolving sustainability issues at an accelerated pace. The goal of presenting the literature in chapter 3 is to equip the reader with a theory of how to accomplish this by focusing on the flow of matter about a complex system.

It will be seen in chapter 7 that describing the model of a sustainable system is similar to the technique of backcasting [33] in that it promotes a system state to aim for. However, as noted by Carew and Mitchell [12], taking advantage of the diversity of sustainability definitions is constructive and therefore the model aims to be adaptable to different perspectives.

The attribute of adaptability within a system also caters for other important system aspects. Firstly, the model itself doesn’t adopt a position of weak or strong sustainability. It allows the preferences of the analyst to explore these positions through creating scenarios. Secondly, it doesn’t limit itself to a select set of metrics or indicators. Many of
the concepts and techniques discussed in section 2.2 can be applied to a system that works from the perspective of the analyst. Thirdly, it facilitates the integration of diverse systems.

The importance of dynamics and understanding how complex systems change over time needs to be at the centre of sustainability assessment and decision-making [10, 11, 92]. This will be addressed by defining a monadic unit based on the concept of time and from which a sustainable system can be built. The problem of obtaining good data sets by which to conduct measurements and assessments that can improve decision making is one of the most persistent amongst the literature. There is no clear solution, but options to work around this by accounting for the presence or absence of links between systems is discussed. Consideration of the structure of system information and knowledge so as to better inform decision-making may help in this respect [93]. An outcome of the model of a sustainable system, therefore, will address how information is organised.

### 2.6 Summary

This chapter presented literature that contributes to developing a sustainable industrial society. It was divided into the major parts of a feedback control loop as a tactic to instill consideration of a typical problem solving process and its applicability to the complexity of describing a sustainable system. Although the difficulties are many and stubborn, there have been significant successes since publication of ‘Our Common Future’ in 1987 [86]:

- ‘Our Common Future’ motivated sustainable development work in spite of, or because of its varied interpretations;
- Much more is known about sustainability (but maybe not development);
- Means to measure, assess and make decisions to promote sustainability in a wide array of systems now exist; and,
- The development of multidisciplinary research and initiatives has highlighted the success and promise of integrative approaches.

Some of the key challenges that persist, then, for progressing sustainable development include:

- A lack of scientific consensus on what constitutes sustainable development and the required quantities and qualities of its components [94];
• The amount of context specific material that exists tends towards developing new disciplines and counteracts an integrative approach [73, 94];
• The amount of sustainable development related material also means finding appropriate indicators is difficult and the quality of information can be dubious;
• Sufficiently accounting for time in indicators, assessments and decision-making processes; and,
• Enthusiasm differs greatly between individuals, nations, industries, political divides [86] making conflicts and trade-offs prevalent.

Overall it is realising that issues of sustainable development constitute a mess [90]. The simple feedback control loop described at the beginning of the chapter is inadequate as a problem solving mechanism. There are systems of problems that require systems of solutions acting in series and parallel with positive and negative feedback loops in the global industrial economy. Dynamic planning strategies that deal with the system holistically are required [90]. In 1998 Meadows [11] wrote, ‘The ratio of change rate to response rate is a critical – and usually critically missing – indicator of the degree to which a system can be controlled’. The ratio of change rate to response rate is re-defined as the ratio of rate of problem generation to the rate of solution implementation within a system here. The following chapters build on the hypothesis that understanding material flow within a complex system provides a way forward for quantifying such a ratio and in turn allows the articulation and management of a sustainable system.
3. Review of literature for modelling a sustainable system

This chapter presents literature for constructing a model of a sustainable system that addresses issues regularly encountered in the sustainability literature and highlighted in section 2.5. Specifically, this chapter includes literature pertaining to:

- Complex systems and problem solving;
- Material waste and thermodynamics; and,
- The plastic waste problem.

It then introduces a laboratory study into the development of a starch based biodegradable packaging film before providing a chapter summary at the end.

Managing complexity and resolving issues of the modern industrial economy is what sustainable development work is about. Creating a sustainable society has tested the limits of human problem solving ability historically and it will continue to do so \[4, 95, 96\]. Therefore, section 3.1 discusses how human society stands in the face of the increasingly complex system it is part of.

The first strategy for handling the complexity of the industrial economy is to concentrate on how matter flows in the system. The ecological principles employed by the Natural Step \[33\] acknowledge that it is the type and density of material distribution and how it flows and transforms that determines the health of biospheric systems. The accumulation of material waste is a prime example where there are concentrations of chemical species dispersed in un-natural quantities. Waste materials represent a stagnation of flow best avoided in a healthy ecosystem. Section 3.2 explores the material waste problem in terms of thermodynamics by looking at the quantity and quality of energy and material flows of the Earth system.

In section 3.3 the example of plastics is used to focus further on material flow. Plastic packaging, in particular, is chosen to illustrate the benefits and pitfalls that a modern product of the industrial economy entails. The rate and volume of global trade could not be possible without innovative packaging methods, and plastics contribute greatly towards that service. As packaging, it works superbly in many situations, and for minimal cost. However, properties such as inertness and superior strength per weight that make it an ideal packaging material are not helpful properties as part of the waste stream.
In section 3.4, an experimental study into the development of a biodegradable starch based plastic film is introduced. Undertaking the experimental study provides insight into how an industrial process delivers a service to the economy. More importantly, it provides experience of the research and development process that advances technical knowledge through gathering, collating and interpreting data, a vital prerequisite in creating meaningful indices for sustainable development [47]. Finally, it provides an opportunity to look at techniques that are used to analyse material flow itself, with a view to modelling it and predicting future flow behaviour. Knowledge of how materials flow about the industrial economy will present options for planning how best to deal with the mess.

3.1 **Sustainability and complexity**

3.1.1 **Messes and wicked problems**

Tainter [4, 95, 96] provides relevant accounts of how historical societies have regularly failed to resolve their challenges as systems of problem solving became more complex. Over time, the simpler problems of a simpler society give way to the more complex and, importantly, greater energy and expense are required to solve them as the systems themselves become more complex. (The continual specialization of research and splintering of disciplines in modern science exemplifies this phenomenon.) What transpires is a scenario of diminishing returns to problem solving as complexity increases. This scenario has represented a limit to earlier societies and their abilities to respond sustainably to challenges. It is a limit that will also determine the efficacy of problem solving abilities within the current society.

The concepts forwarded by Ackoff [90] and Rittel and Webber [97] annunciate reasons for the diminishing returns to problem solving discussed by Tainter [4, 95, 96]. Ackoff [90] suggests:

> ‘Because of an increasing rate of technological change, social and environmental crises are generated and come to a head more rapidly today than at any previous time. Therefore, they require societal responses that are quicker and surer than were required in the past. But our society does not provide them. Its structure and functioning does not facilitate rapid response.’
Suggested solutions to overcome it require knowledge of a society’s position in a system of evolving complexity, and further developing energy for financing problem solving [95]. In light of the diminishing returns, the complexity of the modern industrial economy suggests that significant increases in energy and capital will continue to be needed to achieve sustainable development. Rittel and Webber [97] describe the scenario as a ‘wicked problem’ and in such a case it makes no sense to talk of ‘optimal solutions’. This perspective is similar to that of Ackoff [90] in the discussion of a ‘systems of problems’ or ‘messes’:

‘The solution to a mess can seldom be obtained by independently solving each of the problems of which it is composed… The attempt to deal holistically with a system of problem is what planning, in contrast to problem solving, should be all about.’

Therefore, the model of a sustainable system proposed in chapter 7 equates to a tool for planning, rather than of problem solving, per se. The rapid pace of change in the modern times [11, 98] poses as a major impediment for managing the transition to a sustainable society. It is for this reason that part of the work here explores the possibility of defining the ratio between the rates of change for problems and solutions in a sustainable system.

3.1.2 Complexity

A system ‘can be considered as a conglomerate of related parts such that the ensemble is not only a conglomerate, but it is something more than the conglomerate… everything is, or can be considered a system’ [99]. What are of most interest to the discussion here though, are systems that exhibit complex behaviour or complexity. Like definitions and principles of sustainability, there are numerous formal definitions for complexity without agreement on which may be the best [100]. Nor is there a method for systematically interrelating all the characteristic properties involved [101]. However, Bishop [100] provides a list of features that are often used to characterise systems that exhibit complex behaviour:

- Many-body systems – the number of bodies that yield system complexity depends on the behaviour of individual bodies and their influence upon each other;
- Hierarchy – levels or nested structures (e.g. large scale flow of starch as plastic packaging in economy vs. small-scale flow of starch molecules in plastics extruder);
Irreversibility – distinguishable hierarchies usually result from irreversible processes;

Relations – system entities are coupled via a form of relationship, rather than simply being aggregated (e.g. pile of sand);

Position – dynamics of system entities depend on how they are embedded in their environment as well as the history of the system as a whole;

Integrity – the sum of the system entities is greater than its parts with integrated feedback loops coupling certain parts to maintain the system’s identity;

Intricate behaviour – system behaviour is poised between simple order and total disorder making its description difficult despite not being completely random;

Stability – unity of the system is preserved under small perturbations and adaptive under moderate changes in its environment; and,

Observer relativity – measures and judgements about complexity depend upon the choices of the observer.

Sustainability infers the maintenance of an entity for a period of time. Therefore, an appreciation of the role that time plays in the sustainability of a system is crucial. Time is not explicitly mentioned in the list provided by Bishop [100] above, but it is inferred by reference to ‘dynamics’, ‘processes’ and ‘irreversibility’. Short and long term objectives change as conditions of the present moment change and as generations change.

The space occupied by the systems being developed for sustainability ultimately includes the entire biosphere, but the contribution of smaller spaces cannot be ignored. This means realising the existence and ramifications of a conglomerate of entities and sub-systems of various scales (or hierarchies) that can exist within one another, overlap, or be separated at distance with any number and variety of relationships between them. For example, information now passes freely and quickly between diverse populations across the world and continually alters demands on what the industrial economy should provide. The global distribution of goods through all geographies also means the global distribution of ‘bads’ (a.k.a. wastes) through all geographies.

A result of a process system existing for a certain length of time within a defined space is feedback between and within subsystems. Feedback is ‘conveying information about the outcome of any process or activity to its source [85]. The outputs at one point in time become the inputs at a later point in time for the same system or collections of
subsystems, according to their definition and proximity. Feedback includes cycles of all scales and represents ‘higher degree' types of relationships that form non-linear effects [85]. It is a particularly pertinent consideration in materially finite systems such as those that include the weather, or an industrial economy.

A system of related parts and the consequences of changes in time, space and feedback relationships develop a structural complexity with challenging repercussions for problem solving. This is clearly illustrated by the difficulty encountered by those pursuing sustainable development interests (see chapter 2). Solutions must account for the dynamic and transitory nature of a globally interconnected population. That means large quantities of diverse peoples, and all that that entails, with an uncertain spectrum of needs and desires to cope with as the problems themselves continue to flourish. From a physical perspective, such a complex system displays non-linear and far from equilibrium behaviour [102], the type of behaviour from which self-organising systems and the processes of life have evolved [85].

3.1.3 Resilience and stability

One way of describing the sustainability of a complex system is by observing how it responds to exogenous disturbances. One may ask under what conditions the system is resilient or stable. Furthermore, using the concepts of resilience and stability prescribes a dynamic description of a system. The definitions of resilience and stability forwarded by Holling [103] for studying ecosystem behaviour have provided a starting point for many modern discussions about modern industrial society as well:

‘Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist. In this definition resilience is the property of the system and persistence of probability of extinction is the result. Stability, on the other hand, is the ability of a system to return to an equilibrium state after a temporary disturbance. The more rapidly it returns, and with the least fluctuation, the more stable it is.’

Resilience and stability are not necessarily dependent on each other. Systems can be resilient but have low stability as in the case where there are large but fluctuating oscillations.
Brand [104] suggests that the idea of ecological resilience can provide for a clear conceptualization of ‘critical natural capital’ by establishing exactly how changes resource flows impact the sustainability of the system as a whole. Assessing system resilience can highlight policies that, although assumed to be advantageous, may in fact cause problems if not appropriately tempered. For example, eco-efficiency policies as a single target without parallel policies for more systemic solutions may erode an industrial system’s resilience by limiting its ability to weather a fluctuating market environment [105].

Resilience is not necessarily a good thing if it happens to be describing an undesirable situation or a mess. Resilience is neither desirable in itself nor is it in general a necessary or sufficient condition for sustainable development. More criteria need to be accounted for when designing policies for the sustainable development of ecological-economic systems [106]. When assessing resilience then, it is important to consider the objectives, what types of disturbances are anticipated, the control mechanisms available, and the time scale of interest [107, 108].

Resilience and stability are concepts useful as a nexus for studies of diverse systems to understand each other [106, 109]. They can provide an avenue to explore for developing indicators that provide information on the ability or the likelihood that the current system state can be maintained or improved over time. Indicators that incorporate a measure of resilience provide useful information on system sustainability [110]. Ulanowicz et al. [111], in fact, present an interesting method of quantifying sustainability based on information theory. They seek to determine the resilience of a system by assessing how its dynamics change as the absence or presence of linkages between systems changes. This technique in particular will be revisited for quantifying certain attributes of the sustainable model system in chapter 7.

3.1.4 Information theory
Although humans are made of matter and rely on quantities of matter of certain qualities to maintain their existence, it is their adeptness in the realm of data, information and knowledge that truly distinguishes them from other living entities in the Earth system. The ability to abstract understanding of a phenomenon is one of the most important tools for modern science in analysing complex systems [112]. It has facilitated a significant influence over natural systems [3, 113] for the last 200 odd years, and now can now play a crucial role in tempering that influence more wisely.
Its description as the distinguishing feature of the processes by which humans operate means information theory is inherently interdisciplinary. It can provide a framework for investigating the behaviour of dynamic systems, including nonlinear behaviour and relationships between entities [114], which are necessities for a practical understanding of sustainable systems [95]. Information theory applied from this perspective focuses on the nature of communication in its broadest sense [114].

The relationship between communication and energy was first formulated by Shannon in 1948 [115]. Information can be defined as a measure of ‘distinguishability of different states of a system’ [116], or the ‘amount of order or organisation provided by a message’ [114]. The information in a message was defined by Shannon as the difference between two entropies, or uncertainties: the first associated with knowledge, \( K_n \), before a message and the other associated with knowledge, \( K_n' \), after a message [117]. The differences in order of system components, the differences in system entropies, are articulated as distinguishable signals, or data, that convey information. By associating meaning to this data, humans can attribute a value to the information. In turn, the concept of information can be used to evaluate changes in the quality of resources (that is, the value of resources) available to processes within a system [118]. Essentially, the perceived or meaningful manner in which entities of a system are organised prescribes gradients of value within the system that will drive processes at a rate directly related to overall entropic changes. For example, technology is the artefact of organising entities according to available information and knowledge. It is used to make processes more efficient and effective and hence increases the rate of change of entropy.

The key practical outcome of all this is that the manner in which information and knowledge is organised within a system limits the rate at which its processes can occur. Therefore, the rate at which problems can be solved is reliant on what entities the problem solver distinguishes within a system and the relationships the problem solver understands to exist between them.

In today’s world of information technology, software development and innovative business models, this is the realm of requirements engineering and business analysis. The requirements activity focuses on understanding a business problem, or uncovering a problem to be solved [119]. There are a number of frameworks describing up to seven
primary tasks in the requirements process, but, as an example, Jarke et al. [120] discuss the requirements process broken into three parts: 1) discovery; 2) specification; and, 3) validation and verification. Discovery entails the needs to be addressed by the artefact. That is, what is the problem to be solved. Specification involves producing a representational scheme or model as stakeholders needs and understandings converge. Validation involves ensuring the requirements reflect the intentions of stakeholders, whereas verification assesses the quality of the requirements in terms of technical or formal standards. Some of the critical requirements issues they surmised through an extensive study involving Fortune 500 companies and leading software developers were:

- A focus on the processes of the business;
- A focus on integrating applications rather than developing new ones;
- The need for iteratively developed requirements across multiple levels of abstraction;
- Increasing interdependent complexity; and,
- The need to allow for fluidity of design and evolution of problems and solution after implantation.

It is necessary to recognise the complexity of the system to which the problem and solution pertain in order to obtain greater certainty of information, clarity of knowledge and consensus of opinion to improve decision-making and design suitable plans [90] for managing a sustainable industrial system.

### 3.2 The material waste problem and thermodynamics

The problem of material waste stems from the fact that the existence of the globally interconnected population mentioned above relies on quantities of matter of certain qualities supplied either by the natural environment, or via the economic system they have created from that environment. Such matter takes the form of the food, shelter and clothing that meet their physical needs. An economic system that satisfies these basic physical needs is termed a subsistence economy [121].

Other than these basic needs, humans also have desires, inspired by their imagination. The accumulation and application of knowledge has allowed humans to build an industrial economy that can transform matter into forms aimed to satisfy these additional desires at an accelerating rate. It is at this juncture, in the shift from a subsistence economy to an
industrial one that the problems of material waste in the modern economy take root. Binswanger, founder of the Institute of Economy and Ecology at the University of St. Gallen, Switzerland, says in an interpretative essay of Goethe’s *Faust* [121]:

‘The subsistence economy is adapted to satisfying man’s needs, which are satiable. Its goals are therefore finite. The industrial economy, on the other hand, is adapted to imaginary needs, which can be constantly expanded through man’s fantasy; these needs are insatiable. Inherent, then, in the industrial economy is an infinite starving.’

This ‘infinite starving’ exists within an environment of finite mass, namely that of Earth. As such, there exists a conflict between the infinite and the finite, between imagination and matter. This is the crux of the material waste problem. A sustainable solution to material waste must appreciate this and understand how the economic drive of the problem interacts with the physical constraints imposed by matter and energy as described by the laws of thermodynamics.

### 3.2.1 Thermodynamics of the system

The first law of thermodynamics states that matter and energy can be neither created nor destroyed. They may only change from one form to another. The second law of thermodynamics states that while quantities do not change, quality and order of an isolated system deteriorate over time. In other words, the entropy of an isolated system increases with time as its components tend to disperse according to the available space.

Figure 3.1 provides a simplified illustration of the flow of energy and matter according to the laws of thermodynamics for the Earth system. In thermodynamics a system is defined in space and time and is separated from its environment by system boundaries. A system is called *isolated* when neither energy nor matter cross the boundaries, and *closed* when only energy crosses the boundaries [20]. As such, the Earth is considered part of a closed, non-equilibrium thermodynamic system, where a fixed mass is open to the influence of an external source of what can be subjectively regarded as organised, high quality, low entropy energy in the form of solar energy from the sun [85].

As depicted in Figure 3.1, this energy drives the conversion processes of matter on Earth from ‘Resources’ at an initial time, to ‘Products’ at a later time. Energy that can no longer partake in this conversion process is of low quality, or high entropy, and is discarded as waste heat to outer space.
While discussing biological systems in the essay, ‘What is Life?’ [5], eminent Austrian physicist Erwin Schrödinger suggested how entropy pertains to the functioning of living systems in the following excerpt:

‘Every process, event, happening – call it what you will; in a word, everything that is going on in Nature means an increase in entropy of the part of the world where it is going on. Thus a living organism continually increases its entropy – or, as you may say, produces positive entropy – and thus tends to approach the dangerous state of maximum entropy, which is death. It can only keep aloof from it, i.e. alive, by continually drawing from its environment negative entropy…’

Figure 3.1: Simplified illustration of the total system of matter and energy flow according to the 1st and 2nd laws of thermodynamics for the Earth system – a closed, non-equilibrium thermodynamic system where matter circulates and energy enters then dissipates.

In the context of Figure 3.1, what Schrödinger [5] refers to as ‘negative entropy’ or ‘lower entropy’ is ‘high quality energy’, the ultimate form of which is provided by the sun. Binswanger [121] refers to this ultimate source of ‘negative entropy’ or ‘high quality energy’ as ‘new energy’ in the following excerpt to provide a succinct description of the material waste problem:
'This new energy, in the context of nature and the ecological cycles, is supplied by the sun. But where man, the economic animal, encroaches on nature to the extent he does in the modern economy, the sun's energy is insufficient to counteract the process of entropy. Raw materials become transformed to waste, supplies of raw materials are exhausted, and the burden on the environment mounts.'

3.2.2 Entropy, free energy, available energy, available work, exergy and emergy

It is necessary to state that Schrödinger was aware how inappropriate the term ‘negative entropy’ is in physics, and said that ‘... if I had been catering for (physicists) alone I should have let the discussion turn on free energy instead’ [5] (italics the author’s emphasis). Both authors, Schrödinger and Binswanger, are implying the need for a high quality form of energy, associated with low entropy, as a necessary resource for a living process to proceed. The inclusion of the entropy concept into resource potential is a continuing debate in ecological economics that was begun by Georgescu-Roegen in the 1970s [122, 123]. It has since become a much used and little understood term in the economic context [122, 124]. But it recognises the fact that a particular process will not proceed if there is not a certain type or quality, or structure, of ‘energy’ available to it. For example, it is unlikely that swallowing a mix of soil, water and air from a bucket would be welcomed by the body’s metabolic processes as equally as eating the apple that could be constructed by the tree instead.

Confusion also arises because classical thermodynamics deals with isolated, closed systems heading towards equilibrium and often describes the increasing entropy of such a system as an increase of disorder with time. This seems to contradict the idea of evolutionary ‘progress’ where order increases with time [124]. Therefore, there has been substantial debate about quantifying the concept of the potential utility of a resource with respect to a process.

Free energy, such as in the Gibbs free energy, G, is a thermodynamic term that describes the inherent energy of formation of a compound. Available energy is synonymous with the available work term that is not uncommon in thermodynamics circles and where the concept is often referred to, (not quite correctly), simply as ‘energy’ [124].
Exergy (a combination of Greek syllables for ‘out of’ and ‘work’) was coined by Zoran Rant in 1956 and is used to express the maximum amount of useful energy one can get out of a certain system in a specified state [122]. It is the maximum work that can be obtained from a system when the system is brought from its present state to the state of thermal, mechanical and chemical equilibrium with its surrounding environment [125]. Unlike energy, exergy is not conserved, and can be lost in physical processes [124]. But like energy, it is measured in joules (J).

Emergy is a term adopted by H.T. Odum in 1983 to describe the ‘embodied energy’, or availability of energy (exergy) of one kind (usually solar) that is required directly or indirectly in transformations to make a product or service, or to provide a given flow or storage of energy or matter, measured in emjoules (eJ) [126, 127]. Solar emjoules (seJ) are usually used to express the emergy of a system with reference to the solar origin of energy. An energy hierarchy is used to arrange all transformations of the geo-biosphere in an ordered series. Many joules of sunlight are required to make a joule of organic matter, many joules of organic matter make a joule of joule of fuel, many joules of fuel are required to make a joule of electric power, etc. [126]. Emergy can be expressed as a function of exergy. The main difference is the definition of the system, where exergy of the inputs can be referenced to a single process, but emergy is an accumulation of all direct and indirect inputs referenced to the original input of solar energy [125].

Considering these terms, the accumulation of material waste is associated with increasing entropy of a finite environment, but only by virtue of the thermodynamic consequences of processes that produce the waste. However, it represents a reduction of ‘negative entropy’, or quality (useful) resources, a reduction in exergy or emergy made available to the living organisms of that environment. Up to a certain point, solar energy can moderate the losses through natural processes. But the ‘infinite starving’ of the existing economic system increases the losses faster than what can be naturally reversed. This is not a sustainable situation for living organisms. A system needs to be established where net exergic or emergic losses of an environment can be reversed within a timeframe compliant with what sustainable development requires. Minimizing material waste, ideally eliminating it, is a necessary function of such a system.

Within an engineering type study the preference is for exergy when analyzing a system for its potential to do work. Ayres [128] suggests exergy has two key advantages over the
standard approach of using energy and mass separately. By using exergy as a common measure of inputs and outputs in LCAs, *exergetic efficiency* can be estimated. This provides an indication of the theoretical potential for future improvements for a process and can be used to incorporate awareness of the greater effort needed to extract lower grade or more disperse ores, for example [129, 130]. Secondly, it facilitates a comparison between ‘apples’ and ‘oranges’ making it possible to adequately approximate the exergy content of material waste streams of which composition details are often unknown [55].

3.3 The flow of plastics

‘Ubiquitous’ is a suitable description for the role of plastics in modern life [131], or to put it more poetically, ‘Plastics are the lubricant of globalisation’ [132]. They have a range of unique properties: they can be used over a range of temperatures, are chemical- and light- resistant, and are strong and tough [133]. They can also be worked as a hot melt which contributes tremendously to their processing options and hence their cost. It is impossible to imagine a modern world without plastics [134]. In the context of the benefits and trappings of material flows about the globe, they provide a suitable example for discussing materials in the industrial economy as a whole. Figure 3.2 focuses on the ‘Products’ set of Figure 3.1 and displays selected data for the production, use, disposal and waste management options for entities associated with plastic packaging film.
Figure 3.2: Selected data for the production, use, disposal and waste management options associated with plastics and plastic packaging film.

### 3.3.1 Consumption

Worldwide consumption of plastics has increased from 1.7 Mt in 1950 to 288 Mt in 2012 [135]. The global volume of their production overtook that of steel in 1979, ushering in what may be called the Plastic Age of industrial development [134]. Their manufacture is generally reported to consume about 4% of annual oil and gas production, with an equivalent amount used to fuel the process [133, 136]. As the rapid rise of consumption figures indicate, they are very successful materials. Their variety of mechanical and aesthetic performance properties is largely responsible for this, and they will be responsible for an increasingly important role in the future of human life [133].
3.3.2 Packaging

Packaging in general is the largest application of plastics and accounts for at least a third of total plastic usage [133]. 39% usage was reported for Europe in 2012 [135], a similar amount in India in 2006 [137] and 37% in Australia in 2012 [138]. As packaging films, plastics are indispensable in the global distribution of goods. They contain, isolate, identify and protect them from the point of production to the end consumer [139-141]. Their high strength to weight ratio means they can use less material for a task compared to other packaging options, often at lower cost [142].

3.3.3 Plastic waste

Figures for the amount of plastic in the solid waste stream can vary greatly but it has been estimated between 5 and 15% of the total weight of the landfill waste stream [143]. 2.2 Mt of plastic was reported as part of the waste stream in Australia for 2010/11[144] and 25.2 Mt in Europe in 2012 of which 62.6% was packaging [135]. One available estimate for packaging film says 1.6 Mt of it enters the waste stream of the United Kingdom each year [145].

The properties of versatility and environmental resilience at low cost that make plastics so successful, however, are also those that make them so problematic as waste material. Their fossil oil and gas resources contain stable hydrocarbon molecules that are perfect for their economic purposes but cause them to accumulate as waste, and in the environment they can disrupt the health of life forms and ecosystems [131, 133, 146-148]. Turtles have been known to eat partially bloated bags mistaking them for jellyfish, for example [146].

3.3.4 Litter

It is the single use plastic packaging, typically with a service life of less than one year [138], and its impact as litter that is a particular problem. Andrady and Neal [133] calculated 0.2-0.3% of plastics enter the world’s oceans as litter. A plastic shopping bag has been estimated to have an average working life of 20 minutes [149]. And although 98% of plastic bags are disposed of responsibly in Australia [150], their negative impact in the environment, together with all plastic packaging litter, is disproportionately large. About 13% of packaging, by weight, was reported as being made of plastic in Australia in 2011. Plastic contributes the greatest number of packaging items to the Australian litter stream [151] and plastic in general, the greatest volume [152].
3.3.5 Waste management

For the plastic waste that is managed, resource recovery is preferable to landfill. Being derived from fossil fuels, the inherent value of plastic materials is high and both energy recovery by incineration and material recovery through recycling continue to improve as methods of reducing plastic waste. 35.6% was incinerated and 26.3% recycled in Europe in 2012, a total of 61.9% recovery compared to 59.6% in 2011 [135]. However, there are limits to recovery options. The release of toxic substances into the atmosphere during incineration requires suitable infrastructure to prevent environmental hazards, making it a more successful option in some places rather than others [153]. The difficulty of handling some post-consumer plastic products, like packaging film, can affect their disposition for recycling processes [145]. The loss of material properties through reprocessing and the stability of established markets for recycled products are also limiting factors [153, 154].

3.3.6 Degradable and biodegradable plastics

Other popular options for plastic waste solutions include degradable and biodegradable plastics that are designed to decompose under specified conditions in a certain time. Degradable plastics are typically polyols with additives to accelerate degradation by UV exposure, dry heat, mechanical stress, and/or enzymes, leaving particles of plastic [147]. However, these particles must be completely digested by micro-organisms. If not, there is the potential for environmental and health consequences of ‘invisible’ particles to be greater than those of the original conventional plastics [155, 156].

Biodegradable plastics, according to AS4736-2006 [157] (based on BS EN 13432:2000 [158]), can ‘be broken down by micro-organisms in the presence of oxygen (aerobic) to carbon dioxide, water, biomass and mineral salts or any other elements that are present (mineralization)’ or ‘without the presence of oxygen (anaerobic) to carbon dioxide, methane, water and biomass’. At least 90% conversion of the original material within six months is listed in the standard for aerobic biodegradation, and at least 50% conversion within two months for anaerobic biodegradation, noting the latter refers to biogasification plants that provide a second aerobic stabilisation phase in which biodegradation continues [157].

Production of biodegradable plastics in 2012 was about 0.2% of conventional plastics [159]. In practice, biodegradable packaging materials are most suitable for single-use disposable applications, particularly where it is difficult to separate packaging from
organics in such industries as catering or agriculture, and where the post-consumer waste can be locally composted [155]. But for them to become suitable alternatives to conventional plastics they require more than environmentally sound benefits. They need to become more cost effective, improve management of and reduce disintegration times, clarify appropriate usage and disposal methods, and refine associated national and international standards if their potential is to be realised [146, 147, 155]. Satyanarayana and Chatterji [160] suggest that adhering as closely as possible to nature’s carbon cycle was an important criteria for successfully designing environmentally acceptable materials. Table 3.1 below lists some recently available products that use starch as a resource.
Table 3.1: Starch based plastic products [161].

<table>
<thead>
<tr>
<th>Company</th>
<th>Product name</th>
<th>Material</th>
<th>Application areas</th>
<th>Contact for further details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novamont</td>
<td>Materbi</td>
<td>Thermoplastic starch polymer blends</td>
<td>biodegradable mulch films and bags, thermoformed products, injection molded items, and packaging foam</td>
<td><a href="http://www.novamont.com/">www.novamont.com/</a></td>
</tr>
<tr>
<td>Rodenberg Biopolymers</td>
<td>Solanyl™</td>
<td>Modified potato starch</td>
<td>Injection molded products</td>
<td><a href="http://www.biopolymers.nl/">www.biopolymers.nl/</a></td>
</tr>
<tr>
<td>Biotec GmbH</td>
<td>Bioplast™</td>
<td>Thermoplastic starch</td>
<td>bags, boxes, cups, cutlery, horticultural films, packaging films, planting pots, tableware, trays and wrap film</td>
<td><a href="http://www.biotec.de/engl/index_engl.htm">www.biotec.de/engl/index_engl.htm</a></td>
</tr>
<tr>
<td>Earthshell</td>
<td>EarthShell Packaging®</td>
<td>starch (from sources such as potatoes, corn, wheat, rice and tapioca) along with fiber, other processing agents, air, water and micro-thin biodegradable coatings</td>
<td>foamed trays, plates and packaging films and laminate</td>
<td><a href="http://www.earthshell.com/foam.html">www.earthshell.com/foam.html</a></td>
</tr>
<tr>
<td>Plantic Technologies Ltd</td>
<td>Plantic™</td>
<td>Thermoplastic corn starch polymer</td>
<td>Thermoformed trays</td>
<td><a href="http://www.plantic.com.au">http://www.plantic.com.au</a></td>
</tr>
</tbody>
</table>

3.4 Developing a biodegradable starch based plastic packaging film

The interest in a starch based biodegradable plastic lies in the possible flow of materials from a system of natural processes through a system of industrial and economic processes and back to a system of natural processes, and so on, with a cycle time commensurate with a sustainable system. Figure 3.3 provides an overview of the study. Starch is made of polymeric molecules, as is oil. Unlike oil however, starch is a renewable material found in abundance in plant life, the particular source for this study being wheat. The polymeric components of a starch based biodegradable plastic can partake in the
natural carbon cycle, and therefore starch plastics offer the possibility of a suitable material cycle time.

(a) Problem scenario
- oil and gas based plastic waste accumulates

(b) Proposed solution
- starch based plastic waste doesn’t accumulate

(c) Experimental study
- plastics processing

(d) Viscosity model
- characterizes material flow
- Eq. 6.7

\[ \eta = K' \left( \dot{\gamma}_w \right)^{m-1} e^{(E_a/RT)} \]

Figure 3.3: An overview of the experimental study presented in chapters 4-6.
In Figure 3.3(a), the cycle time of carbon is large enough to approximate to linear flow, from oil and gas reservoirs to plastic waste. This is in contrast to what is illustrated in Figure 3.3(b) where the cycle time of the starch based material components aims to be within two years. The proposal is cyclic flow of matter rather than linear flow of matter.

The system boundary for the experiments includes the process of plastic film manufacture from the point of selecting and combining the raw materials through to blown film extrusion (see Figure 3.3(c)). Remembering this study was conducted near the advent of marketable biodegradable plastic products, there is a significant benefit in studying the entire plastic film process – that is, points at which economic and commercial advantages are possible can be identified at a process system level. It also has the advantage of exposing a single investigator to a variety of observations of industrial interest.

Consistency of product is a prerequisite for the success of industrial processes and that requires extensive knowledge of both the materials and transformations that a particular process involves. In the case of blown film extrusion, an unstable bubble, or an instability, leads to inconsistent bubble diameter, which can in turn produce poor mechanical and physical properties in the film [162]. Stability is the ability of a system to return to an equilibrium state after a temporary disturbance [103]. A stable bubble means a uniform product can be extruded with minimal interruptions. It is therefore desirable to know the operating parameters and corresponding values which will yield a stable process. The capacity to predict the likely flow behaviour of a combination of molecules (polymers and additives) is desirable in that respect and the science used for constructing models for this purpose is rheology, the study of the flow and deformation of matter.

Looking at Figure 3.3(c), the flow properties of the material between the ‘compound (reactive) extrusion’ stage and the ‘blown film extrusion’ stage directly impact the parameters of stability. The viscous behaviour of the material at that point is an initial condition of the film blowing stage. Therefore, a model for viscosity as a function of extrusion temperature and shear rate is forwarded in Figure 3.3(d).

For the purposes of this discussion it is important to note that focusing on viscosity as opposed to other material properties makes sense for a number of reasons. First and
foremost, and in the light what role material flow has in the thesis, it is a direct measure of a materials tendency to flow. If Figures 3.3(a) and 3.3(b) are compared, it can be envisaged that the viscosity of the flow of carbon in the former is very much greater than the latter. Of course, viscosity is not usually used for such macroscopic descriptions, but the concept of a resistance to flow remains. From such a perspective, if material waste increases in a certain stream of material flow, its viscosity can be understood to increase, and it would be of interest to determine how the viscosity can be altered. It is the contemplation of such system analogies which makes viscosity an interesting property to study in context of the dissertation’s aims.

Following a series of reactive extrusion and blown film extrusion trials, selected samples were subjected to slit die rheometry to generate data for th empirical viscosity model shown in Figure 3.3(d), Eq. 6.7, which is described completely in chapter 6. Analytical methods, namely differential scanning calorimetry (DSC), gel permeation chromatography (GPC), moisture absorption tests and tensile strength tests are used to further evaluate material properties of the samples. In combination with the rheological viscosity model results, the material property analyses are used to explain molecular transformations and behaviour of the samples during extrusion over a range of shear rates (screw speeds) and temperatures.

3.5 Summary

This chapter has presented material that will be used to construct a model in chapter 7 as a response to the findings of the literature overview in chapter 2. That is, this material will be used to investigate the possibilities of integrating systems and incorporating time effects into a tool capable of providing insight to the ratio between the rate of problem proliferation and the rate of solution implementation in the context of sustainability. The history of problem solving and complexity provides an awareness of how difficult the problem is in an social sense. The dynamics of complex systems, including their conditions of resilience and stability, outlines the practical realities and constraints concerning the extent to which system integration is possible.

Since the flow and transformation of matter in complex systems is fundamental for sustaining life, a logical first strategy for simplifying the complexity of the total system is to focus upon material flow throughout that system. The importance of material flow and transformation is also the premise of The Natural Step principles [17]. What influences
that flow and transformation? Conversely, what inhibits that flow and transformation? The accumulation of material waste is a problem for sustainable development and opens up questions about how natural processes and economics inter-relate.

The materials most symbolic of the pace and diversity of life in the modern industrial economy are plastics. Their prevalence in global society is underwritten by how, in what form, where and for how long they appear in the waste stream. Plastic packaging is a competent facilitator of modern trade and commerce, but it is also a toxic contributor to litter present in all the world’s oceans.

The next three chapters present a laboratory study into the development of a biodegradable starch based plastic packaging film. It is included in its entirety because it envelops problem solving, material flow and transformation, and plastic packaging waste together in a way that can be investigated from world trade down to the level of molecules. It is important to understand, also, how the common practice of research and development fits into the overall goal of sustainable development. Ruiz-Mercado et al. [163] write in their work associated with the GREENSCOPE methodology, ‘Sustainability assessments require data such as experimental results, physicochemical, thermodynamic and toxicity properties of the employed substances, material and energy flows, operating conditions, costs and equipment specification to evaluate the indicators.’

Considered together, sections 3.2-3.4 view systems of decreasing scale of material flow: from that of the industrial economy, to that of plastics within the industrial economy, down to the molecules within the plastics. One of the defining characteristics of successful sustainability initiatives, whether they are definitions, indicators, decisions or actions, or others, is that they are scalable. The understanding of what has been presented in this chapter will be combined with the observations of the following experimental work to describe a conceptual model of a sustainable system in chapter 7.
4. Starch based biodegradable plastic packaging film:

Literature review

The following pages provide an overview of literature relevant to designing experiments for developing a starch based biodegradable plastic packaging film. It is split into three sections:

- Plastic packaging film technology;
- Starch properties and processing technology; and,
- Starch and the development of degradable plastics.

The first section provides an understanding of how plastic packaging film fits into the modern economy. That is, it discusses the services it provides and the production technology involved. It also presents some of the rheological modelling techniques used to theoretically describe the film blowing process. The second section of the chapter looks at physical and chemical properties of starch molecules as well as some rheological models that have been developed for describing the viscosity of starch extrudates. Section three of the chapter presents a background of the early development of starch being used in plastics.

4.1 Plastic packaging film technology

A brief history of plastic film production, why packaging is needed, what plastics are used when, and methods of production are discussed below. The blown film extrusion process is paid particular attention because of its predominance in plastic packaging film manufacture, as well as being the process used for the ensuing experiments.

4.1.1 History of packaging film production

The first commercially successful synthetic plastic was produced from cellulose nitrate, a derivative of the plant material cellulose. In 1869, John Wesley Hyatt found that it could be plasticised with the addition of camphor, and the new material, celluloid, was suitable as an inexpensive substitute for ivory. Amongst a number of applications such as for combs, billiard balls and buttons it was used for photographic film. It had excellent clarity, strength, resistance to moisture and dimensional stability. However, its flammability limited its viability as a useful film [164].
The most important development in films was the production of regenerated cellulose. Matthias Eduard Schweizer discovered the first process for dissolving cellulose and subsequently regenerating it with the cuprammonium rayon fibre process [164].

Regenerated cellulose remained an unrivalled leader in films up to the middle of this century when polyethylene became the first to challenge cellulose film. Later, other polymeric materials such as polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) either diminished the markets for cellulose film or created new markets of their own.

A key to their success was the process of extrusion. The plastics extrusion process began developing from the middle of the 1930s. Extrusion of blown polyethylene film first appeared in the USA in 1939, and later in Europe in 1951 [165]. Initially, the clarity achieved was poor and application was limited to industrial packaging, such as for equipment inside wooden crates and the packaging of electrical resistors. When high clarity films were finally developed, markets opened for polyethylene film as display packaging for items such as textiles, woolens and soft toys. The falling cost of polymer production at the time made polyethylene film the cheapest transparent film available [164].

Despite polyethylene’s other desirable properties, its low stiffness compared to regenerated cellulose film left regenerated cellulose film relatively unchallenged until the advent of polypropylene film in 1959 with its good clarity, stiffness and barrier properties [164]. Other films have since been developed to cater for specific requirements but their high cost relative to polypropylene has lessened their impact.

Acceptance of plastic film was helped by the continually decreasing cost of oil, up until the early 1970s, leading to gradual replacement of more traditional packaging materials such as paper. In fact, in 1979 the global volume of plastics production outstripped that of steel [165], suggesting that this replacement might not have been all that gradual. Increasing prices tend to slow the rate of increase of plastics consumption [164]. But for both technical and economic reasons, as well as performance, plastics are still, and will continue to be, competitively priced in relation to other materials [133].
4.1.2 The role of packaging films

Packaging films are used universally to contain, isolate and identify packaged goods. They offer protection for products from a potentially destructive environment on the way from the producer or manufacturer to the consumer. Although the types of hazards differ depending on the product, selection of packaging has to involve consideration of mechanical, climatic, biological and social hazards from the initial handling and transportation, and must also cater to customer appeal [139-141].

There are three main factors to consider for protection [141]:

- The severity of the immediate environment;
- The sensitivity of the goods to that environment; and,
- The barrier properties which the package is able to interpose between them.
  (Barrier properties combine those of the film itself as well as how the package is sealed.)

Plastic packaging films tend to offer little protection against mechanical hazards. The mechanical hazards of handling, transport and storage are provided by a bulk, outer containment, usually rigid, to prevent crushing. Wood-based board, that is timber or cardboard, are able to supply mechanical protection far more cheaply than is possible with any thin plastic. Plastic film can, however, provide damping of vibrational forces during transportation [141].

Packages from the producer are separated for storage after transportation. A second pack to collate and contain a number of the primary packs is convenient at this point to improve handling and storage. The primary pack is designed to protect against temperature, light, relative humidity, atmospheric gases, mould spores and bacteria. The secondary pack can also absorb some of these hazards. A high temperature climate accelerates all reactions including the diffusion of gases and water, whilst daily fluctuations in temperature can produce condensation. Plastic film is able to minimise this moisture reaching the goods and pigmented plastic film easily protects against light. In the sales area, most of the protection relies on the primary pack, where vapours, gases and invisible biota are all possible dangers [140, 141].
When it comes to selecting a plastic film for packaging purposes, Oswin [141] suggests, ‘Not all goods face the same hazards and the art of packaging lies in selecting a packaging material with a profile of protective properties matching the needs of a particular product - at least cost.’

**4.1.3 Applications for plastic packaging films**

Plastic film has provided ideal properties to cater for many packaging requirements. Figures for U.S. plastic film consumption in 1989, for example, show approximately 90% of all plastic film produced is used for packaging. Food packaging accounts for about 35% of packaging film and merchandise and garbage bags account for a further 26% of all packaging film [140].

The primary function of packaging is to contain the product, making the versatility of plastic films with regards to sealing methods extremely valuable. Plastic films can be used for straight wrapping, shrink wrapping, sachets, bags, pouches, heavy duty sacks, skin packaging and blister packs. The variety of uses for plastic films in packaging is extensive. Details are provided in texts by Oswin [141], Osborn and Jenkins [140] and Briston [164]. From these publications, a brief summary of applications for different polymers is presented below.

**4.1.3.1 Low density polyethylene (LDPE)**

LDPE accounts for approximately 75% of the total amount of thermoplastic films used in packaging and is regarded as the most important packaging film [164]. Food packaging accounts for most of LDPE film used in packaging. Merchandise and garbage bags account for the second largest LDPE packaging market. Another large market is that of heavy duty sacks for packaging of fertilisers, peat, coal as well as the plastic pellets themselves.

Shrink wrapping is an ever increasing outlet for LDPE. The concept of shrink wrapping is based on the fact that plastic maintains a ‘memory’ from stretching during processing. When reheated the film reverts to its original dimensions. This is done by loosely wrapping the object with film then heating the film, commonly with hot air.

LDPE is also used to pre-package heavier items such as potatoes while its barrier properties, particularly to moisture, allow its use in packaging lettuce and other green
vegetables. However, LDPE is not good at allowing the permeation of respiratory gases which still continue to be produced after packaging. This is alleviated by punching holes in the film to allow continued transfer of oxygen and carbon dioxide and to prevent the build up of moisture in the bag. Low temperature toughness of LDPE makes it ideal for packaging frozen foods such as peas, beans, etc. Its soft feel allows it to be used for textile packaging where the customer is able to feel the texture without opening the bag.

4.1.3.2 High density polyethylene (HDPE)
HDPE has widespread use as merchandise bags and garbage bin liners due to its better barrier properties to moisture and greases, as well as its strength and light weight. HDPE is used extensively for wrapping meat, fish, meat pies, etc.

4.1.3.3 Polypropylene (PP)
PP is used in both oriented and unoriented forms, the former making up the bulk of the PP packaging film market. Oriented PP film (OPP) has superior clarity, better barrier properties and higher impact strength than unoriented PP. Coated OPP films and films coextruded with other polymers are used where good barriers to oxygen and moisture are important, such as for packaging biscuits, potato chips, confectionary, snack foods, tobacco and cigarette cartons. Cast PP finds use in medical packaging for medical disposables and where its relatively high temperature resistance allows its use in autoclaves up to temperatures around 135°C.

The better clarity of the film is an advantage over LDPE in retail applications. However, its higher cost limits its use to only when necessary. Yet, recent advances in technology and the building of larger scale production facilities have made the cost of PP almost equivalent to LDPE.

4.1.3.4 Polyvinyl chloride (PVC)
The largest market for PVC film is in shrink or stretch wrapping of fresh cuts of meat. The film must provide high oxygen permeability to allow the formation of the oxymyoglobin responsible for the purple colour of fresh red meat. The film must be able to withstand low temperatures, be shrinkable and have good clarity and gloss. PVC is used for packaging poultry, fish, other frozen foods and to a lesser extent, produce.
4.1.3.5 Polystyrene (PS)
PS has excellent transparency and dimensional stability. In gauges below 75 μm it is used for window cartons in retail applications. It is also used for over-wrapping of fresh produce because of its gas permeability.

4.1.3.6 Multilayer Films
Generally, monolayer films do not always provide the required properties for the protection of the packaged item, particularly in the food industry. Even in applications for shrink films, for blister and skin packaging and bags, the surface often needs to be modified to provide sufficient adhesion for printing ink. In food applications, the gas barrier properties of a single layer of film are often not adequate, so a layer of high barrier polymer is added. Heat sealing in particular requires a layer of a polymer with lower melting point.

Additional processing is typically performed using a separate machine by a manufacturer (or converter) other than the resin or film manufacturer. The film must be unwound from the roll, processed appropriately and then rewound onto a roll. However, when economically feasible and the added complexity can be tolerated, the films can be coextruded or laminated in a single process. Use of multilayer films tends to complicate statistical data, so a film containing three layers is usually considered as three separate films where statistical data is available [140].

4.1.4 Plastic film extrusion
The production of plastic packaging film is divided between two major extrusion methods, namely film blowing and casting [166]. The former of these has transpired as the dominant method of film production, and consequently has been paid the most attention in theoretical and experimental studies. Each of these methods is described below. An overview of the theory behind the film blowing process is also included.

4.1.4.1 Extrusion
Equipment for film extrusion consists of an extruder with an appropriate die attached, equipment to cool the molten film, haul-off machinery and a wind-up unit [166].

The polymer is fed to the extruder in granular or pellet form through a hopper. The polymer is melted both by external heating bands around the barrel of the extruder and through viscous heating due to shearing the material between the screw, the inner wall of
the barrel and the material itself. In some cases, viscous heating provides enough energy to produce the melt and external heating is only required for start-up. The extruder then mixes and pumps the homogenous melt to the die exit.

Screw design is important when considering the type of material to be extruded and different designs are used for each polymer type. They are characterised by their length to diameter ratio (L/D ratio) and the compression ratio. The compression ratio is the ratio of the volume of one turn of the screw at the hopper end to the volume of one turn at the die end. Length to diameter ratios are typically between 15:1 and 30:1 and compression ratios from 2:1 to 4:1.

The screw is usually divided into three sections - feed, compression and metering. The feed section takes the pellets or granules from the feed sections to the heated part of the barrel. The compression section is where the depth of the thread gradually decreases to cause a volume compression of the melting granules. This leads to better mixing of the melt and more uniform heat distributions. The metering section, where the diameter of the body of the screw is constant, transports the material to the breaker plate and the die exit. The breaker plate holds a coarse screen in place before the die to remove any contaminating particles in the melt, or contains gel-like material until it melts. It also reduces memory effects when the polymer melt leaves the extruder exit. Particular aspects of the extrusion process are discussed further in a number of references [166-168].

4.1.4.2 The film blowing process
Film blowing is a method of producing thin sheets of thermoplastics rather more rapidly and economically than is possible with the casting process [169]. Figure 4.1 illustrates the process. It involves biaxial stretching of a polymer melt exiting an annular die attached to the extruder. The extruder is responsible for heating, pumping and mixing the melt before the die exit. A take-up device, usually a variable speed motor connected to the nip rolls, provides stretching of the polymer in the axial direction. The ratio of the axial velocity at the nip rolls and the velocity at the die exit is referred to as the turn-up ratio (TUR).

Inflation of the bubble by introducing air to the centre of the tube at the bottom of the die during start-up provides stretching in the transverse, circumferential or 'hoop' direction. An air ring cools the outer surface of the bubble to solidify the melt at a point above the die
exit called the freeze or frost line. The ratio of the final bubble diameter at the freeze line and the diameter of the die is referred to as the blow up ratio (BUR). The height of the freeze line is determined by the rate and temperature of the cooling air [170]. Traditionally, it has been assumed that no significant deformation of the film takes place above this point. The validity of this assumption has been tested with mathematical models by Cao and Campbell [171, 172]. They concluded that simulations must continue above the freeze line if physical properties of the film are to be predicted with any accuracy using blown film analysis.

Figure 4.1: A schematic of the film blowing process.

The bubble passes between guide rolls and through the nip rolls where it is pinched closed. The pressure inside the bubble is maintained at slightly above atmospheric. The flat tube is then wound onto cylindrical cores or the edges trimmed to produce two flat films.
Biaxial stretching of the film governs the orientation of the macromolecules to provide desirable physical properties in the final product such as tensile strength, tear resistance and heat seal characteristics. Three important processing variables, namely: the rate of stretching, the rate of cooling, and the air pressure inside the inflated bubble, affect the orientation of macromolecules and hence the degree of crystallinity [173-179].

The quality of the film is usually measured by the uniformity of its thickness and the optical clarity. Uniformity of film thickness requires steady uniform output from the screw extruder driving the flow, a well-designed die held at a steady uniform temperature with uniform die gap, air cooling as well as low friction at the guide rolls or plates [166].

4.1.4.3 The cast film process
This process is also referred to as slit-die extrusion or flat film extrusion. The molten polymer is extruded through a slit-die and then quenched in a water bath or passed onto a chilled roller. It is critical to quench the film quickly after leaving the die to minimise thickness variations as the melt can tend to draw in an uncontrolled and non-uniform manner. Rapid cooling also forms smaller crystallites and hence a clearer film. Briston [164] and Osborn and Jenkins [166] provide further details of the process.

The water temperature, when a quench bath is used, should be kept constant to provide the best film properties. For a constant extrusion temperature, lower water temperatures improve slip and anti-blocking\(^2\) properties while higher temperatures lead to better physical properties and a film that is easier to wind without wrinkling.

The slit-die is designed with the melt fed to the centre of the die into a large manifold relative to the die exit. The manifold shape and design helps to achieve mechanical rigidity and uniform temperature across the die. A coat hanger design compensates for the drop in pressure towards the outer edges of the die. The melt needs to be of low viscosity to aid in this compensation and hence flat film extrusion uses higher temperatures. This in turn requires the extruded material to have substantial thermal stability. The die needs to be precisely machined and well polished internally to prevent any flow and consequent gauge variations. The opening between the die lips can be adjusted by bolts along its length. Perfect uniform residence time for the melt across the

\(^1\) Blocking is the undesirable tendency for the film to stick together.
die is still difficult to achieve and so the melt can degrade, gel and block towards the outer ends of the die necessitating frequent shut down for clean-up.

4.1.4.4 **Comparison of cast film and film blowing processes**
The choice of one method over the other is primarily dictated by the desired properties. Process variables tend to control film properties such as clarity, thickness and thickness uniformity, and film flatness. The polymer system usually determines toughness, stiffness, tear strength, heat sealability and gas barrier properties [166]. The processing steps that significantly differ in the two methods are quenching and melt drawing. In the film blowing process the melt is cooled over a relatively long period leading to a more crystalline and hazy film when compared to cast films. Greater crystallinity leads to greater film stiffness and improved barrier properties. The effect is similar within the cast film process when chill-roll quenched films are compared to water quenched films. Faster quenching rates for cast film also help increase throughput for thicker films.

The greater extent of melt drawing in film blowing can inhibit control over the uniformity of the film thickness and flatness. However, it also leads to a greater extent of orientation of the macromolecules in the film to increase tensile strength, toughness and stiffness. Generally, the film blowing process is chosen for applications where lower quality film can be tolerated and where technical support is minimal [166]. Table 4.1 below lists some of the advantages of each of the methods.

Table 4.1: Relative advantages of the film blowing and cast film processes.

<table>
<thead>
<tr>
<th>The Film Blowing Process</th>
<th>The Cast Film Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved mechanical properties.</td>
<td>Higher possible outputs.</td>
</tr>
<tr>
<td>Width adjustment is easier and edge trimming due to necking problems is not necessary.</td>
<td>Better optical properties.</td>
</tr>
<tr>
<td>Lower cost for wider films. (Equipment costs increase rapidly as cast film width increases.)</td>
<td>Better control of thickness and thickness uniformity.</td>
</tr>
<tr>
<td>Cheaper and more compact dies for films of comparable width.</td>
<td>Easier and more flexible operation.</td>
</tr>
</tbody>
</table>
4.1.5 Theory of the film blowing process

Film blowing is a non-uniform multi-axial extensional deformation process involving material rheology, heat transfer, aerodynamic effects, boundary conditions, initial conditions and other interactions [180]. Consequently, attempts to model the process with the aim of predicting the final properties of the material, will confront significant complexities and difficulties.

The initial approach taken to modelling the flow of the melt was that of Pearson and Petrie [181, 182] in 1970. They focused on the region between the die exit and the freeze line, the point past which there is assumed to be no further deformation of the polymer. ‘The basic assumptions made are that the forces controlling the flow are the viscous forces arising in the steady axisymmetric isothermal flow of a homogenous Newtonian liquid, and that the film is thin enough for variations in the flow field across it to be ignored, and for the velocity gradients to be approximated locally by those of a plane film being extended biaxially’ [182]. Much of the work in film blowing theory since has surrounded adjusting the two assumptions in italics to obtain a truer representation of the process.

4.1.5.1 Kinematics

A schematic for the co-ordinate system used to describe the kinematics and dynamics of the bubble is presented in Figure 4.2.

![Figure 4.2: The co-ordinate system used for the tubular film extrusion analysis.](image-url)
For this example, ‘1’ is taken as the machine direction, ‘2’ as the circumferential or ‘hoop’ direction, and ‘3’ as the thickness direction in local cartesian co-ordinates. The rate of deformation tensor takes the form,

\[
\mathbf{d} = \begin{bmatrix}
    \frac{\partial v_1}{\partial \xi_1} \\
    \frac{\partial v_2}{\partial \xi_2} \\
    \frac{\partial v_3}{\partial \xi_3}
\end{bmatrix}
\]

where \(\xi_1, \xi_2\) and \(\xi_3\) represent the machine, transverse and thickness directions, and \(v\) is the respective velocity. Assuming continuity, Pearson and Petrie [181] express the local velocity gradients as,

\[
\frac{\partial v_1}{\partial \xi_1} = \left( \frac{\partial v_2}{\partial \xi_2} + \frac{\partial v_3}{\partial \xi_3} \right) = -\frac{Q \cos \theta}{2 \pi R H} \left( \frac{1}{dz} \frac{dH}{dz} + \frac{1}{dz} \frac{dR}{dz} \right)
\]

\[
\frac{\partial v_2}{\partial \xi_2} = \frac{1}{R} \frac{dR}{dt} = \frac{Q \cos \theta}{2 \pi R H} \frac{1}{dz} \frac{dR}{dz}
\]

\[
\frac{\partial v_3}{\partial \xi_3} = \frac{1}{H} \frac{dH}{dt} = \frac{Q \cos \theta}{2 \pi R H} \frac{1}{dz} \frac{dH}{dz}
\]

where \(Q\) is the mass extrusion rate, \(R\) is the bubble radius at any height \(z\), \(H\) is the film thickness at any height \(z\), and \(\theta\) is the angle between the axis of the bubble and a tangent to the surface of the bubble.

### 4.1.5.2 Dynamics

Membrane theory was used by Pearson and Petrie [181] to derive the following expressions for the force balance on tubular film.

\[
F_L = 2 \pi R H \sigma_1 \cos \theta + \pi \Delta p \left( R_L^2 - R^2 \right)
\]
where $F_L$ is the drawdown force, $\sigma_{11}$ is the stress in the machine direction, and $\Delta p$ is the pressure across the bubble calculated by Equation 4.6.

$$\Delta p = \frac{H\sigma_{11}}{R_1} + \frac{H\sigma_{22}}{R_2}$$  \hspace{1cm} (4.6)$$

$R_1$ and $R_2$ are the principal radii of curvature and $\sigma_{22}$ is the stress in the transverse (circumferential or hoop) direction.

$$R_1 = -\left[1 + \left(\frac{dR}{dz}\right)^2\right]^{1/2} = -\frac{\sec^2\theta}{d^2R/dz^2}$$  \hspace{1cm} (4.7)$$

$$R_2 = -R\sec\theta$$  \hspace{1cm} (4.8)$$

### 4.1.5.3 Heat balance

An example of a heat balance to account for non-isothermal conditions, assuming constant properties through the film thickness takes the form of Equation 4.9.

$$\rho c Q \cos \theta \frac{dT}{dz} = -2\pi R \left[h(T - T_c) + \varepsilon \lambda \left(T^4 - T_s^4\right)\right] + Q\Delta H_f \cos \theta \frac{dT}{dz}$$  \hspace{1cm} (4.9)$$

$T$ is the mean temperature of the film, $T_c$ the cooling air temperature, $T_s$ the temperature of the bubble surface, $\rho$ the density of the melt, $c$ its heat capacity, $h$ the heat transfer coefficient, $\varepsilon$ the emissivity, $\lambda$ the Stefan Boltzmann constant, $\Delta H_f$ the heat of crystallisation, and $X$ the fraction of crystallinity [183].

Petrie [184] replaced the Newtonian fluid model of Pearson and Petrie [181, 182] with two Maxwell type models derived from the general Oldroyd equation. Petrie [185], Gupta [186], Gupta et al. [187] and Luo and Tanner [188] included non-isothermal effects into such models, the latter also using the Leonov model. Cain and Denn [189] extended modelling efforts to include a Marucci fluid model. Cao and Campbell [170, 172] were the first to consider a form of the Maxwell model to include downstream cooling effects, coupling a viscoelastic fluid model below the freeze line with one for an elastic solid above it. Rather than a freeze line though, they refer to a plastic to elastic transition (PET) region, beginning where the surface temperature of the film reaches the melt crystallising
temperature and ending where the yield stress of the crystallised phase exceeds the effective applied stress. Preceding this, the film is in the liquid phase of the melt, and above the PET the dominant elastic deformations are considered negligible.

Ashok and Campbell [190] used an upper convected Maxwell equation of state to describe the amorphous phase and a perfect plastic-elastic model with yield stress to propose a two-phase interpretation of the process. Liu [191] and Liu et al. [192] included the influences of crystallinity with a term in a viscous constitutive equation that also included a relaxation time.

All models of the film blowing process that concentrate on the viscoelastic nature of the fluid below the freeze line and the changes associated with cooling the material up to that point have reasonable success in representing the fundamental flow principles of the process. Non-isothermal power law fluid models for viscosity have been used in conjunction with the basic relationships formulated by Pearson and Petrie [181, 182] to obtain good results by means simpler than those required to tackle the difficulties of more inclusive models. Han and Park [173], and Han and Shetty [193] obtained promising agreement between theoretical predictions and experimental data with such models. Kanai and White [183], Yamane and White [194], and Kanai [195] accounted for crystallinity in their power law fluid models. All of these authors have found good agreement to various degrees between their proposed models and available experimental data. However, it is difficult to conclude if the increased energy required to solve more complex descriptions of the process justify any improvements in model predictions.

A very successful predictive but labour intensive model was proposed by Alaie and Papanastasiou [196] where the material was analysed by means of an integral constitutive equation accounting for multiple relaxation times, shear-thinning, extension-thinning or thickening and for the shear-prehistory inside the die. Energy and momentum equations were used to investigate temperature effects to a point of maximum inflation, beyond the freeze line. Model solutions compare very well with experimental data for polystyrene published by Gupta [186]. The algorithm is suitable for studying ways of optimising the film blowing process, given the rheological and thermophysical characteristics of the material and the range of applied processing conditions. Film orientation and microstructure can also be studied because the analysis can predict residual stresses.
Very few publications pay attention to the aerodynamic effects of the cooling air. Although the possible importance of cooling air ring design and the associated changes in heat transfer are brought up by Petrie [185], its role in the process is not given significant attention. Cao and Campbell [170] and Campbell et al. [197] did, however, improve simulation results when cooling air effects were accounted for near the die exit.

4.1.6 Stability of the film blowing process

It is of industrial importance that a quality film with the desired properties be produced consistently. This is achieved by maintaining a stable film bubble during the extrusion operation. An unstable bubble, or an instability, leads to inconsistent bubble diameter, which can in turn produce poor mechanical and physical properties in the film [162]. The result is an unmarketable product.

Han and Park [162] found the shape of the bubble to be very sensitive to disturbances in mass flow rate, air pressure, temperature, and take-up speed. Two types of instability were observed during the experiments. During uniaxial stretching, a draw resonance phenomenon or pulsing similar to what has been observed in melt spinning studies occurred. Under biaxial stretching, a wave type instability occurred. Stability eventually returned when the disturbance was small, but the unstable flow continued when the disturbance was greater than a critical value.

Supporting these results, Han and Shetty [193] experimented with step changes in either the air pressure inside the bubble or take-up speed on bubble shape. A disturbance in the take-up speed influenced bubble stability far more than a disturbance in air pressure, and a decrease in melt temperature helped stabilise the bubble after a disturbance by way of increasing the elongational viscosity.

Stability of the film under the influence of axisymmetric disturbances was modeled by Yeow [198] for a Newtonian fluid. However, it is difficult to readily compare these results with those of experimental studies because of the inconsistency of terms used to represent results. Experimental comparisons later by Minoshima and White [199] showed little agreement, due to the simplifications of the model.

Kanai and White [183] studied the film extrusion of LDPE, LLDPE, and HDPE. As well as the kinematics, dynamics and heat transfer of the process, stability profiles were related to
the rheological properties of the three resins, particularly their respective elongational viscosities. Amongst many factors influencing the process, deformation-rate hardening was shown to be a stabilising influence. This conclusion complements results of Han and Shetty [193] where decreasing temperature helped stabilise the bubble after a disturbance.

Again using samples of LDPE, LLDPE, HDPE, Minoshima and White [199] considered the influence of molecular weight distributions. Long chain branched polyethylenes (LDPE) were found to provide the widest range of operating conditions conducive to stability, followed by the broad distribution linear polyethylenes, and then the narrow molecular weight distribution resins (HDPE and LLDPE). They also noted that increasing frost line height broadened the possible operating conditions, but decreased the stable region of operation.

Molecular differences between high pressure and low pressure polyethylene were related to experimentally observed differences in bubble properties during film blowing by Han and Kwack [200] and Kwack and Han [201]. Resins having lower elongational viscosities gave greater draw-down ratios, indicating a better processing ability. Tensile properties were found to correlate with BUR and TUR during film blowing.

Results supporting these fundamental relationships in film blowing have since been published by Fleissner [202] for HDPE samples, who also noted the effect of strain hardening on stability, Takashige and Kanai [203] for nylon 6 film and Ghijsels et al. [204] for various polyethylenes.

Sweeney et al. [205] successfully used video techniques to quantify the degree of instability during film blowing and thus provided a method generally applicable for minimising variations in product properties. Their results for LLDPE and LDPE confirmed the notion that long chain branching significantly influences the stability of the material during film blowing.

4.2 Starch properties and processing technology

Included in this section is an overview of starch properties, its uses, extrusion of starch-based materials, and methods of modelling the rheological properties of starch extrudates.
4.2.1 Physical and chemical properties of starch

Starch is the major polysaccharide reserve material of the plant kingdom and the second largest biomass produced on the earth, next to cellulose [206]. It is a natural energy reserve stored as granules in varying amounts in roots, tubers, seed and other parts of the plant. The granules can exist as spheres, ellipses, platelets etc. and have dimensions between 1 and 200 μm [206-211].

Starch is principally a mixture of two polymeric carbohydrates - amylose, a molecule containing a small number of long-chain branches (it has been described as linear often in the literature)[212] comprised of anhydroglucose units linked through α-D(1→4) glucosidic bonds, and amylopectin, a highly branched molecule with α-D(1→6) branch points. Branches may be around 20-30 anhydroglucose units in length [206-211, 213]. Figure 4.3 illustrates the molecular structure of each polymeric component.

![Molecular structure of starch](image)

Figure 4.3: (a) linear amylose (1,4-α-D-glucose); (b) branched amylopectin – linear amylose chains with (1,6-α-D-glycosidic) branches.

The chemical structure of starch, however, will differ depending on botanical source and genetic background [206]. Typical starches contain between 18 and 30% amylose. Potato and tapioca starches are at the lower end and corn and wheat starches at the
higher end of this range [207]. Trace amounts of proteins, lipids and inorganic matter are also present. The molecular weight of the amylose fraction has been reported anywhere between 100,000 and 1,000,000. Amylopectin can have a molecular weight of several million [210, 213]. Details of the organisation of the molecules in the granule continues to be debatable. However, it is mostly accepted that amylopectin constitutes the crystalline component of the granules, with the short branched chains occurring in the amorphous regions [214]. In native granules, around 70% of the structure is thought to exist as crystalline regions [208, 210].

The crystalline regions have been paid the most attention in research. Their existence is readily observed through their birefringent properties that produce polarisation crosses under microscopic examination with polarised light [207, 208]. These regions produce two X-ray diffraction diagrams representing A and B starches as reported by Wu and Sarko [215, 216]. A third structure sometimes found known as C starch, is thought to be a combination of the former two. Both A- and B-amylose used in structural studies are based on parallel stranded, right-handed helices in the crystal structure [215, 216]. Wu and Sarko reported that A-amylose contains only a quarter of the water molecules that are present in a unit cell of B-amylose, probably accounting in part for the denser packing structure of the former. Which form exists fundamentally depends on the chain length and water content [214].

The lesser studied amorphous regions contain the amylose fraction and amylopectin branch points. The amylose is found in the central part of the granule between crystalline lamellae [217]. Trommsdorff and Tomka [218, 219] justified the existence of amorphous regions through hydrogen bonding between the hydroxyl groups within starch, and between these hydroxyl groups and water molecules.

The chemistry of the molecule is governed by the end groups of the polymer chains. The reducing end of the molecule contains an anhydroglucose unit with one primary and two secondary hydroxyl groups and an aldehydic reducing group in the form of an inner hemiacetal. The opposite non-reducing end of the molecule has one anhydroglucose unit containing one primary hydroxyl and three secondary hydroxyls. All other anhydroglucose units have one primary and two secondary hydroxyls [207].
Hydroxyl groups cause starch to generally behave as an alcohol during chemical reactions. The presence of such a large number of hydroxyls imparts considerable influence over the reactive nature of the starch molecules. They provide hydrophilic properties and therefore an affinity for moisture and dispersability in water. However, the effect in water is reduced by the linearity and consequent mobility of the chains which allow hydrogen bonding and van der Waals forces to exist between hydroxyls in adjacent chains. They become oriented in a parallel fashion and the affinity of the polymer for water is decreased. These intermolecular forces stabilise pairs of double helices that give rise to the A and B structures previously discussed [214].

4.2.2 Uses of starch

The nutritional value of starch for humans and farm animals has long been an important reason for the cultivation of starch rich crops such as maize, wheat, potato, rice, tapioca and sago crops. The possible pre-treatments and modifications that starch can undergo ensure that its commercial uses are extensive [207-209]. Table 4.2 lists some of the important properties and uses of modified starches.

Table 4.2: A list of some examples of modified starches [208].

<table>
<thead>
<tr>
<th>Modified Starch</th>
<th>Treatment</th>
<th>Advantages over natural starch</th>
<th>Examples of use in food</th>
<th>Examples of (non-food) Industrial use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pregelatinised</td>
<td>heat/moisture</td>
<td>cold-water soluble</td>
<td>pie fillings, ‘instant products’ coatings</td>
<td>oil drilling, mining</td>
</tr>
<tr>
<td>Acid-thinned</td>
<td>Acid</td>
<td>low hot paste viscosity, high gel viscosity</td>
<td>gums, jellies</td>
<td>textiles, laundry starch</td>
</tr>
<tr>
<td>Oxidised</td>
<td>Hypochlorite</td>
<td>increased clarity, reduced set-back</td>
<td>gravy/sauce thickeners, jellies</td>
<td>paper, textiles, spray starch, adhesives</td>
</tr>
<tr>
<td>Hydroxyalkyl ethers</td>
<td>propylene oxide</td>
<td>increased clarity, increased stability</td>
<td>salad dressings, pie fillings</td>
<td>paper and textile sizes</td>
</tr>
<tr>
<td>Esterified</td>
<td>acetic anhydride</td>
<td>reduced set-back, increased clarity, forms films/fibres</td>
<td>frozen foods</td>
<td>packaging, film</td>
</tr>
<tr>
<td>Monophosphates</td>
<td>phosphoric acid</td>
<td>increased stability to freeze/thaw cycles</td>
<td>frozen foods, infant formulae</td>
<td>paper, textiles, metal refining</td>
</tr>
<tr>
<td>Cross-linked, e.g. di-starch phosphate</td>
<td>phosphorous oxychloride</td>
<td>increased stability to heat, pH, shear and freeze-thaw cycles</td>
<td>wide range of canned and frozen foods</td>
<td>paper, metal sequestrates</td>
</tr>
</tbody>
</table>
4.2.3 Starch extrusion

The extrusion of starch in the food industry has been practiced since 1935 [220]. It is from the perspective of this industry that nearly all of starch extrusion literature, is written.

During extrusion, starch passes through an environment of relatively high pressure, high temperatures and mechanical shear forces. The introduction of energy leads to gelatinisation, melting and fragmentation of the starch. The cumulative result of these reactions is often referred to as starch conversion. A review by Lai and Kokini [221] covered work on the physicochemical changes and consequent rheological properties of starch conversion during extrusion. Temperature, screw speed and process geometry establish the transient shear forces that are induced during extrusion and that contribute to starch conversion processes.

In the extruder, water diffuses into the starch granules in the initial part of the screw chamber. As the chamber fills and the material reaches the melting zone, starch granules are compressed, deformed, and begin to melt and lose their crystalline regions. Viscous dissipation of mechanical energy at this point leads to breakdown of the starch molecules, particularly amylopectin. Gelatinisation occurs as the product is in the shear zone under influence of both external heating and viscous heating inside the barrel. This involves the breakdown of hydrogen bonds between the starch molecules themselves, allowing water molecules to diffuse into the anhydroglucose units to form loose bonds with available hydroxyl groups [222].

Gelatinisation is difficult when possible at low moisture contents and the effect of heat cannot gelatinise starch during the short residence times during extrusion. However, the shear forces induced inside the barrel physically tear apart the starch granules allowing faster transfer of water into the starch molecules [223]. The shear forces within the extruder lead to the loss of crystallinity by disruption of molecular bonds, rather than by the penetration of water [224]. Changes in crystallinity can be observed with optical microscopy using polarised light [207, 208] or through X-ray diffraction patterns [215, 216].

DSC studies by Gomez and Aguilera [225] concluded that native starch was no longer present in amounts detectable by DSC when no peak was observed between 25 and 115°C, indicating the complete loss of the original granule structure, and therefore its crystallinity. When this occurs, the granule is said to be ‘destructorised’ [226].
Dynamic DSC techniques were used by Wang et al. [227] to develop a useful correlation describing the role moisture content has regarding the conversion rate for gelatinisation and melting of starch. A water content below 40% at extrusion temperatures produced pseudo-zeroth order kinetics for starch conversion.

The starch conversion associated with mechanical disruption can be attributed to many extrusion parameters and their interrelationships [220, 228-231]. Bruin et al. [220] reviewed the fundamental influences of extruder design and screw speed on flow patterns, flow rates, residence time distributions and power consumption. Mercier and Feillet [228] studied temperature, moisture and amyllose content influences in the extrusion process. Results from tests for the amount of water soluble content and susceptibility to $\alpha$-amylase showed increases with increased extrusion rate and temperature.

Chiang and Johnson [229] studied the effect of starch moisture content, temperature, screw speed, and die nozzle size on gelatinisation during extrusion. Temperature and moisture content were found to be significant variables. Moisture content alone did not significantly affect starch conversion at lower temperatures (65-85°C) but became significant at temperatures above 95°C. Increasing die nozzle size, or decreasing extrusion pressure, decreased starch gelatinisation. Molecular fragmentation was also shown to occur during extrusion.

Similar results were obtained by Owusu-Answah et al. [232] who found the interaction between temperature and moisture the most significant variable regarding starch conversion, followed by temperature alone, then moisture, and screw speed. Burros et al. [223] studied the kinetics of starch gelatinisation through DSC techniques. The results confirmed temperature and moisture as significant variables, as did those of Bhattacharya and Hanna [230], and Wang et al. [227].

The molecular changes, or fragmentation, induced through mechanical shear in a low moisture environment govern many of the extrudate properties. The mechanism of fragmentation is believed to be mainly limited debranching of amylopectin, which significantly decreases the overall molecular weight without measurably changing the percentage of $\alpha$-(1→6) bonds, as determined by the relative number of end reducing
groups [233-235]. Fragmentation itself can be perceived by a decrease in viscosity and an increase in solubility of starch extrudates [228, 233-238].

GPC has enabled a number of researchers to deduce influences of extrusion parameters on molecular fragmentation [222, 224, 233-236, 238-241]. Generally speaking, the molecular size distributions show that high molecular weight material decreases as moisture content and extrusion temperature decreases and as screw speed (or mechanical energy supplied) increases. Any changes in molecular weight distributions become less significant with subsequent extrusions [234].

4.2.4 Modelling rheological properties of starch extrudates
The rheological properties of starch materials depend strongly on processing variables such as temperature, moisture content, screw speed, screw configuration and the consequent molecular transformations. Rheological properties are also related to the size, shape and molecular weight of a fluid’s molecules at any point in time.

Mathematical relationships have been developed from molecular and physical entanglement theories to predict rheological properties of synthetic polymers [242, 243]. As pointed out by Lai and Kokini [221] though, the analogy between petrochemical polymers and starch polymers is difficult to extend this far. Thermoplastic petrochemical polymers undergo reversible melting and irreversible polymerisation reactions during extrusion, whereas the starch polymers also undergo irreversible gelatinisation with network entanglement and fragmentation. Extruding starch with low water content produces a mixture of small amounts of gelatinised and melted starch as well as fragments of starch granules existing in the extruder simultaneously [244].

Predicting extrudate properties with functions describing the competition between gelatinisation, melting and fragmentation reactions is understandably difficult. However, and in spite of the differences between the two, a number of techniques commonly used to characterise petrochemically derived polymers have been used to determine the rheological properties, especially viscous properties, of starch with considerable success. These include capillary and slit die work [222, 231, 245-253].

The viscosity model for cooked cereal doughs developed by Harper et al. [254] has provided a dependable beginning for modelling the effects of shear rate, temperature and
moisture content on starch-based materials. The power law equation is commonly used to
describe the pseudo-plastic behaviour of materials that show a change in viscosity with
shear rate. Harper et al. [254] included temperature effects with an Arrhenius relationship
that predicts an exponential dependence of viscosity to the inverse of the temperature.
Moisture effects were included by way of a semi-empirical exponential relationship. The
model takes the form of Equation 4.10.

\[ \eta(\dot{\gamma}, T, M) = C_1 (\dot{\gamma})^{C_2} e^{C_3/T} e^{C_4 M} \quad (4.10) \]

where \( \eta(\dot{\gamma}, T, M) \) is the viscosity of the fluid as a function shear rate, \( \dot{\gamma} \), absolute
temperature, \( T \), and moisture content, \( M \). \( C_1, C_2, C_3 \) and \( C_4 \) are empirically determined
constants. The model constants were determined with a fractional factorial experimental
design with the results of the experiments analysed by way of multiple linear regression.
The model fitted experimental results satisfactorily.

Remsen and Clark [255] modelled the viscosity of cooked dough similarly for temperature
and shear rate effects and included a term for reaction time in the extruder. Equation 2.10
was also adapted by Chen et al. [91] to model soy dough extrusion rheology, and by
Levine [256] to estimate extruder output and power consumption. Davidson et al. [244]
and Diosady et al. [257] used a measure of molecular weight change to incorporate the
effects of mechanical degradation on viscosity.

Morgan [258] obtained good agreement with experimental data using results from a
generalised model allowing the viscosity of extruded protein dough to be calculated from
the effects of shear rate, moisture content, temperature, temperature-time history and
strain history. An extensive and generalised model was also successfully used by Mackey
and Ofoli [259].

Specific mechanical energy (SME) (Whr/kg) is a term that has been used in conjunction
with viscosity models to estimate the overall starch conversion during extrusion [222, 249,
251, 260]. It brings with it the possibility of providing a convenient term relevant to scale
up techniques and is expressed as:

\[ \text{SME} = M\omega/m \quad (4.11) \]
where $M$ is the torque (N.m), $\omega$ is the rotation speed (rad/s) and $m$ is the mass flow rate (kg/h). SME is the power used to pump the material through the die divided by the total mass flow rate [249]. The power to pump the material increases with the pressure drop, shear stress and the amount of material in the extruder [222]. SME was incorporated into viscosity models by Senouci and Smith [249], who concluded the models were accurate enough for engineering calculations.

Vergnes et al. [261] described the thermomechanical energy used to shear the molten material in the extruder as a means of understanding molecular degradation. They found there was a clear relationship between the degree of macromolecular degradation and intensity of treatment. Intrinsic viscosity decreased and the water solubility index increased with increasing thermomechanical energy input.

Della Valle et al. [260] also used a balance of mechanical and thermal energies to quantify the specific energy delivered (SED) to the product. A relationship between this energy and the intrinsic viscosity measurements was found, but the water solubility index was less influenced. Their conclusions suggested that SED was able to improve on the accuracy of SME results for predicting viscous properties because it included thermal inputs and losses.

4.3 **Starch and the development of degradable plastics**

This third section looks at the initial rise of interest in starch for developing limited lifetime, degradable plastics. The initial part presents opinions about the possibilities of degradable plastics in general succeeding in the market place. The following parts concentrate on the methods of using starch in particular for producing degradable plastics. Generally speaking, starch can be incorporated into plastics as granules, in virgin form or chemically modified, behaving as a filler within the continuous phase or matrix polymer, or it can be destructurised and plasticised to form thermoplastic starch.

4.3.1 **Starch in degradable plastics**

Starch was first considered as a filler in conventional thermoplastics in the 1970s to reduce reliance on oil supplies and to impart degradability in the product. Westhoff et al. [262] prepared starch-filled PVC and tested physical properties and susceptibility to microbial attack. Plastic compositions containing up to 50% starch by weight were concluded to give physical properties comparable to that of PVC with a similar amount of inorganic filler,
but with the advantage of being readily attacked by microorganisms in the soil. This work was continued with an investigation into the potential of various starch graft copolymers as degradable PVC fillers [263]. The physical properties of the plastics were comparable to PVC with similar amounts of inorganic filler. All plastic samples supported mould growth and it was concluded that such plastics should degrade more rapidly than conventional PVC plastics.

Otey et al. [263] produced cast films from a water dispersion of starch and poly vinyl alcohol (PVA) with a coating of PVC or a vinyl/acrylic copolymer for the purpose of agricultural mulch film. Glycerol was used as a plasticiser and formaldehyde as a cross-linking agent. The films exhibited properties acceptable for agricultural mulch film.

Early patents covering starch-filled plastics were assigned to Griffin [264-268]. In 1988, Koch and Roper [269] listed starch as a filler or reactive component in synthetic polymers among new applications of starch. More recently, a starch filled co-extruded polyethylene film was patented by Knott and Gage [270].

Griffin [271] provides a useful background on the development of starch filled plastics. It has an advantage over inorganic fillers in that its density is closer to synthetic polymers, therefore it can occupy a similar volume with less weight. The limit of how much starch can be blended is relies on the type of product. In the case of thin plastic films, the amount of starch is limited by the ratio of the granule size to the thickness of the film. Therefore, small granule starch is more appropriate as a polyethylene filler [206].

One method of improving biodegradation involved irradiating starch filled LDPE to generate free radicals to increase autoxidation [272]. Extruded starch filled LDPE samples were prepared by Shah et al. [273] to investigate the dependence of physical properties and degradation mechanisms on thermal treatment, ultra-violet radiation, starch content and additive content. They concluded ‘various environmental factors have synergistic effects on the degradation mechanism of starch-LDPE.’

Starch polymers can be used as extenders and replacements for petroleum based polymers through graft polymerisation [274, 275]. There are many examples of graft polymerisation of starch with synthetic polymers and copolymer blends. Fanta [213]
describes the more common materials and methods of producing graft and block copolymers with starch.

Graft polymers are often prepared by generating free radicals on starch. Free radicals are either initiated by chemical means or high energy irradiation. Starch graft copolymers have been prepared with styrene [274, 275], caprolactone [276-278], methacrylate [279, 280] and acrylamide [281] to name a few.

Blends of starch with ethylene acrylic acid (EAA) have been used to produce potentially biodegradable films [282-285]. Combinations of this copolymer, conventional plasticisers and optionally polyethylene have been blown into film using conventional extrusion equipment [283, 286, 287]. Extruded blown plastic films containing up to 40% starch and varying amounts of EAA and LDPE were tested for biodegradability in laboratory and river environments [288]. Analysis of FTIR spectra showed that the susceptibility of the plastics to degradation increased with starch content.

Disadvantages of starch-EAA blends include the large amounts of water required for premixing, ammonia as a by-product, and they are not necessarily 100% biodegradable. Starch ethylvinyl alcohol (starch-EVA) blends are easier to prepare and promise greater biodegradability [289]. The physical properties, water absorbance, degradation and rheology of these materials have been published [289-292]. The effects of various polyols as plasticisers with starch-EVA copolymers were published by Westhoff et al. [293]. Polyols of longer chain length, such as sorbitol, proved to behave more effectively as plasticisers than the smaller glycerol molecules.

Patents pertaining to the development of thermoplastics using starch include those for graft/blended copolymers [294-309], and those for degradable blown films or injection mouldable items [300-306]. A very inclusive patent was assigned to Warner-Lambert Company [307] in 1992 with 868 claims. It covers the use of destructurised starch in any amount and another polymer to give a polymer combination that can be formed under heat and pressure into consumable articles.
4.3.2 Thermoplastic starch (TPS)

Research in TPS has grown significantly over the past 20 years because it is economic, abundant, renewable and biodegradable [310, 311]. Extruding TPS can be regarded as a combined process consisting of extrusion cooking and plastic compounding [308] and much processing work on TPS draws upon the research into extrusion cooking of starch discussed above in section 4.2.

Raw starch combined with plasticisers such as water and glycerol can be converted to a homogenous molten state using conventional polymer processing techniques and since water and glycerol are inexpensive, they are often amongst used in production [312-318]. Tomka [309] considered starch extruded with water as the sole plasticiser in the system, as is often the case in starch food materials. Rheological properties of the melt and thermo-mechanical transformations were related to the water content of the system. Starch was plasticised with water, glycerol or xylitol in a twin screw extruder by Kirby et al. [313]. Tensile properties and changes from brittle to ductile behaviour were related to increasing plasticiser content. Lourdin et al. [314] approached the phenomenon of anti-plasticisation in starch films plasticised with glycerol and water. The influences of glycerol in decreasing the glass transition temperature and changing tensile properties were attributed to relaxation mechanisms in the polymer matrix.

A review by Xie et al. [253] provides a significant collection of starch processing literature. In it they note the high SME needed to process starch thermoplastics and the issues of using water as a plasticiser still limit rheological measurement techniques. This means that cone and plate or parallel plate often used to study conventional thermoplastics can not be used because of the loss of water at processing temperatures. Therefore, most research focuses on using extruder-fed slit die or capillary rheometry [253, 312]. The rheology of TPS was studied with capillary rheometry by Willet et al. [319] and the effects of temperature, moisture content and plasticiser additives were related to the melt viscosity in terms of power law parameters. Xie et al. [320] used a twin-screw extruder to compound samples and then a single-screw extruder with a slit capillary die to measure rheological properties of corn starches with different amylase/amylopectin ratios. Data was fitted to a power law model to compare the flow properties of the samples. The samples all exhibited shear-thinning behaviour with the power law index, n, increasing with temperature, a similar trend seen in many conventional polymer systems. They explained
the higher viscosities observed with the higher amylose content starches through the higher gelatinisation temperatures these types of starches have. A multipass rheometer was used by Tajuddin et al. [312] to study starch/water/glycerol combinations. Multipass rheometers have the advantage of requiring only a small sample (compared to twin- or single-screw extruders) and are fully enclosed and pressurised to avoid problems with water volatility. It was shown that shear-thinning behaviour increased with the glycerol/water ratio. Villar et al. [290] reported the rheological properties of starch/poly(ethylene-co-vinyl alcohol) blends to behave similarly to starch-based food materials. van Soest et al. [321] investigated the influence of molecular mass on the properties of extruded TPS and concluded importantly, that polymer chemical principles were successful in explaining the mechanical behaviour of the different molecular weight TPS materials.

Liu et al. [322] found that degradation via extrusion causes the size distribution of starch molecules to narrow and converge toward a maximum stable size due to both the selective scission and the maximum stable size concept. This means starch melt may achieve a stable structural (and thus rheological) state under processing with shear and heat treatments. If a consistent and stable molecular structure could be readily produced, processes more susceptible to stability issues, such as film blowing, could be better controlled.

Blown film extrusion Thunwall et al. [315] extruded two potato starches (one native, the other treated via hydroxypropylation and oxidation) with water and glycerol to produce plastic film. They found that the native starch was significantly more difficult to extrude with problems of stickiness, foaming and bubble rupture. However, they were able to establish a space of operating parameters based on moisture content, glycerol content and temperature. The better performance of the treated starch was attributed to the lower molecular weight of the oxidised starch. Zullo and Iannace [318] studied the effect of starch source, supplier and types of plasticiser on the physicochemical and mechanical properties of blown films. They are also one of the few that reported extensional viscosities for the materials. Of the samples prepared, they found using 30% urea/formamide plasticiser mixture with high-amylose starch produced the best film.

Hydroxypropylated and oxidised starches were combined with glycerol and water to form films via casting, compression moulding and blown film extrusion by Altskar et al.[317].
Film blowing produced the greatest degradation and the morphology, as studied with electron microscopy revealed complexity and phase separations on different levels. However, the fine network structure observed in the case films was not present in the blown films, primarily due to the thermomechanical treatment imbued by the latter process. The tensile properties of extruded starch films was performed by Li et al. [311]. Waxy, normal and high-amylose starches were used. Molecular and crystalline structures were investigated by size-exclusion chromatography and X-ray diffractometry. The high amylose starch samples produced a higher elongation at break than the other two starches. It was concluded that mechanical properties are possibly more reliant on starch recrystallisation than on crystallinity remaining from ungelatinised starch granules.

4.4 Summary of experimental related literature

The initial part of the chapter described what is required of a plastic packaging film in the marketplace and provided the criteria for what is expected of any new packaging film product, such as the one that is the subject of the experimental study. An overview of the equipment and extrusion processes involved with the production of a packaging film provided a background of what happens during the extrusion of polymer products. Of particular interest is the theoretical modelling of the blown film extrusion process. A number of rheological models describe the flow of the polymer during processing to predict the final mechanical properties of the plastic film. There are also many that aim to predict the effect that process parameters have on bubble stability, and hence the effect of the operation on producing a consistent, marketable product.

The section on starch properties and processing highlighted the similarities between synthetic polymers and starch. These are not few since synthetic polymers are derived from gas and oil that were historically plant life. However, comparisons in the way they behave during processing, and the rheological techniques used in both the plastics industry and food industry for modelling their flow behaviour, are also of particular interest for researching an economical biodegradable plastic. That has allowed research into TPD to flourish in the last 20 years. There has been extensive work in characterising rheological properties of different starches combined with various ratios of water, glycerol and other types of plasticisers by a number of different methods. Included amongst them are studies on the starch/water/glycerol systems in blown film extrusion.
The experiments described in the following chapter are designed on the basis that TPS may be processed with conventional plastics processing equipment, and that TPS may be analysed using similar principles to those used for analysing conventional plastics. The discussion of the experimental results in chapter 6 takes advantage of the literature reviewed here.
5. Starch based biodegradable plastic packaging film: Experimental design

Starch is an attractive alternative to petrochemically-derived polymers for producing biodegradable plastic packaging because:

- The linear amylose and branched amylopectin polymers in starch are similar to petrochemical polymers such as polyethylenes. and behave in a similar manner during processing with conventional extrusion equipment;
- Starch is a renewable resource;
- Starch is susceptible to processes of biodegradation;
- Starch is in abundance as the major energy reserve material of the plant kingdom; and,
- Starch is inexpensive.

This chapter describes the materials, apparatus and processes used to produce a number of starch based plastic samples for potential application as a biodegradable packaging film. It also includes a description of the slit-die rheometry equipment used to collect data for the rheological analysis and viscous modelling presented in chapter 6.

5.1 Experimental aims

Figure 5.1 illustrates the system boundary and process stages considered for the experimental design and analysis.

Figure 5.1: The system of process stages used for producing thermoplastic starch samples.

One key reason for wanting to consider the process from ingredients to product is to gain a better idea of the production costs of the materials developed. In the market place, a thermoplastic starch film must be comparable in price to those packaging films that already exist if it is to be commercially successful (an increase in price of no more than 10% is
suggested by Griffin [271]). It must also offer a clear benefit over and above performing as a packaging film if it is to compete with materials as proficient as LDPE.

It is also a key aim to produce a product that adheres as closely as possible to nature’s carbon cycle, an important criteria for successfully designing environmentally acceptable materials [160]. Therefore, it was decided to maximise renewable feedstocks and product biodegradability (rather than degradability) for these experiments and observe the extent to which these materials could yield a suitable plastic film using conventional plastic film extrusion technology.

Fixed costs were kept at a minimum by processing with a single screw extruder. Twin screw extruders that have substantially higher capital costs have traditionally been used to process starch in the food industry because of their superior mixing abilities. However, many new designs of single screws have become available that attempt to improve the extent of mixing in the extruder without resorting to the cost of a twin screw extruder. The screw used in this study (supplied by Axon Australia Pty Ltd), has twelve slots cut perpendicularly either side of six flights in the compression zone. Such a design is used to increase the mixing time of the melt in the extruder by allowing some of the melt to flow to a preceding turn in the screw through the slots.

Variable costs were minimised by using the most inexpensive and locally available starch source - native wheat starch. Costs of all additives processed with the starch were chosen with minimal cost in mind. Additives capable of increasing extruder throughputs are considered to reduce production costs. Additives were kept to a minimum and with the conditions of biodegradability in mind. More detail regarding their selection is included in section 6.1.

In short, the experimental aims were:

- observe the total process from material selection to final product;
- select materials suitable for producing a biodegradable plastic;
- maximum biodegradability;
- maintain minimal fixed and variable costs throughout;
- measure product properties of samples; and,
- measure processing properties of samples.
The results were used to assess the success of producing a starch based plastic packaging suitable for reducing plastic waste.

5.2 Materials and apparatus

5.2.1 Materials

All starch used throughout the course of the experiments was untreated native wheat starch kindly donated by Goodman Fielder Pty Ltd. A series of papers by Wootton and Mahdar [323-325] provides various properties of Australian wheat starch. Starch is assumed to contain about 30% amylose and 70% amylopectin on a dry weight basis. The moisture content of the wheat starch received was consistently around 13%. This is the value taken as the inherent moisture content of all the starch received and used for experiments.

Distilled water and glycerol were extruded with the starch to act as plasticisers. Glycerol was provided by Campbell Brothers Ltd.

Sample additives chosen as a result of preliminary extrusion trials to aid in processing and improve thermoplastic properties, namely, sodium hydroxide (NaOH), trisodium trimetaphosphate (TSTMP), methyl(triethoxy)silane, and succinic anhydride were all obtained from Sigma-Aldrich Inc. and used as received.

5.2.2 Granulation

A convenient method of combining the sample constituents homogeneously in quantities large enough for laboratory extrusion was by spraying the liquid and soluble additives on to the starch as it flowed in an open pan granulator.

Samples were prepared based on 2 kg of native wheat starch. Initially enough water was sprayed on to the dry mix to give a moisture content of about 33-34% of the total mass. This is near the water binding capacity of dry wheat starch [326]. Individual starch granules conglomerate and grow as the sample is dried under an infra-red heater at a temperature of 40-45°C in the bulk of the flowing mix. Drying times were approximately 1.5 hrs, varying upon the desired moisture content and the relative humidity of the immediate environment. Moisture content was monitored by regularly analysing samples.
with a moisture determining balance equipped with an infra-red heater (Sartorious, model MA-30).

The result after combining the starch with the additives was around 2.3 kg of spherical granules that moved at a steady rate through the feed hopper of the extruder, avoiding the feed problems that unsteady the flow rate of material into the extruder. The sample granules were sealed and stored at room conditions in LDPE bags until further use.

5.2.3 Extrusion – apparatus and compounding conditions
A single screw extruder supplied by Axon Australia Pty Ltd was used for extrusion of all samples. The screw diameter was 25 mm (L/D = 30) with 12 slotted flights in the compression zone to increase mixing time in the extruder. The temperature along the barrel was set and maintained with heating bands in five separate temperature controlled zones. To prevent any gelled or melted material choking the feed zone, it was supplied with cooling water and heating bands in the first zone of the barrel were not used.

Granulated samples were compounded with a set temperature profile of 70, 80, 100, 120°C for the heating zones from the die to the feed zone respectively. (Compounding can be regarded as a process of reactive extrusion, where the materials react at elevated temperature and pressure). The screw speed was 40 rpm for all compounding of the granular starch mixtures, giving a mass flow rate of approximately 5.4 kg/hr. These extrusion conditions were the result of preliminary trials that are discussed as part of the results in section 6.1.

A string die with 8 x 2 mm diameter holes was fitted to the extruder for compounding to produce strings that were cut into pellets with rotating knives at the end of the extruder. The pellets were measured for moisture content in a similar manner to the granules described in section 5.2.2 then sealed and stored in LDPE bags until further use.

5.2.4 Blown film extrusion - apparatus
An extruder as described above in section 5.2.3 was used to pump the thermoplastic melt through a stainless steel annular film extrusion die, manufactured by Axon Australia Pty Ltd for film blowing experiments. The diameter of the annular die was 40 mm with a die gap of 1 mm. It was of a common design with the melt from the extruder entering the spirals of the mandrel through four equally spaced inlets at the base of the mandrel.
Vertically adjustable nip rolls controlled by a variable speed motor provided axial drawing of the bubble. Air for bubble inflation and cooling was supplied at room temperature (25°C). The extruder settings such as temperature profile and screw speed for blown film extrusion differed to that for compounding and are discussed as part of the results in section 6.2.

5.3 Sample analysis techniques

5.3.1 DSC

A Perkin-Elmer DSC-7 equipped with a liquid nitrogen cooling system was used to study the thermally associated transitions of chosen samples. Where sample extrudates were studied, pellets of samples were frozen with liquid nitrogen and ground into a fine powder with a coffee grinder for improved sample response during DSC. About 20 mg of sample was hermetically sealed in stainless steel pans. An empty pan was used as a reference and the tests were carried out under a nitrogen atmosphere. The instrument calibration was performed with indium ($\Delta H_{\text{fusion}} = 28.59$ J/g, melting point ($T_{\text{onset}}$) = 156.60°C).

In one group of tests, the presence of a glass transition was investigated by heating the sample from 30 to 200°C at 5°C/min and held at 200°C for one minute to remove any thermal events that may have occurred during the preparation and storage of the samples. The sample was then cooled to -50°C at 100°C/min and held for one minute at -50°C to freeze the sample in the amorphous state. A second scan from -50 to 200°C at 5°C/min was performed to reveal any transitions.

A second group of experiments was performed to confirm that starch granules had ‘destructurised’. A determined mass of the sample was combined with water in a ratio of 1:2. Excess water promotes the presence of a gelatinisation peak associated with the native starch structure [327]. The samples were heated from 30 to 130°C at 5°C/min. All scans for both sets of experiments were duplicated.

5.3.2 GPC

The molecular weight distributions of native wheat starch and some extruded samples were determined qualitatively using a Waters Associates Chromatograph equipped with a differential refractometer Waters 410 detector. Samples of 10-20 μg were dissolved in dimethyl sulphoxide (DMSO) in 10 ml volumetric flasks. DMSO was also used as the
eluent. The volumetric flowrate of eluent was 1 ml/min. Data were collected at intervals of 1s and at a testing temperature of 70°C.

5.3.3 Moisture absorption tests
Sample pellets were pressed into 1 mm thick sheets at 160°C and cut into rectangular strips 75 mm x 25 mm as described in ASTM D570-81 for moisture absorption tests. The samples were pre-conditioned in a vacuum oven at 50°C for 24 hours and the dry mass recorded before being immersed in distilled water. Readings were taken over 24 hours by removing the samples from the water, drying off the excess water with tissues and the moisture absorbed determined as a percentage of the original dry mass. The samples were replaced in the vacuum oven at 50°C for 48 hours and weighed to determine the amount of material lost. The tests were performed in triplicate.

5.3.4 Tensile tests
Tensile measurements were performed using an Instron universal testing apparatus. Sample pellets were pressed into 1mm thick sheets at 160°C and cut into dog bone test specimens as described in ASTM D638-91, with a gauge length of 7.5 mm. Samples were stored at 25°C and 65% relative humidity until testing. The cross-head speed was 1 mm/min with a data sample rate of 5 s⁻¹. Five specimens were tested for each sample.

5.4 Slit-die extrusion
Starch polymer melts are very complex and undergo a number of physicochemical transformations during extrusion [221]. Such transformations are intertwined with the melt’s flow properties. A number of researchers have used both capillary and slit die rheometry to investigate changes in the melt viscosity with shear rate at several temperatures for both natural and synthetic polymer melts. Single screw extruders [91, 241, 251, 255-257], twin screw extruders [250, 258-261], and pre-shearing rheometers that can control the extent of thermo-mechanical treatment before viscosity measurements [248, 261] have all been used to pump starch-based melts through a die to determine the pressure profile along an axis of flow. Results from these experiments are usually gathered to develop models that predict the viscosity of the extruded starch material as a function of shear rate, temperature and moisture content [232, 246, 249, 254], as well as the time-temperature effects that influence the extent of melting, gelatinisation and fragmentation [244, 255, 257-259].
A number of samples (see section 6.1) were prepared to investigate changes in viscosity induced by the processing conditions and additives used for their preparation. The data were used to develop models that expressed viscosity as a function of shear rate and temperature. Samples A, B and C were fed to the extruder in the granular form for slit die extrusion. Two further samples of B and C were first compounded through reactive extrusion (see section 5.2.3) and then the pellets extruded through the slit die. These samples are referred to as samples Bx and Cx respectively.

The slit-die was made of stainless steel. A schematic of the die is shown in Figure 5.2. The slit was 2 mm high, 25 mm wide and 125 mm long. A slit width to height ratio, (W/H), of 12.5 and length to height ratio, (L/H), of 62.5 were assumed large enough to provide fully developed flow within the slit and therefore side wall effects could be neglected during data analysis. A slit height of 2 mm produced pressures in the extruder that approached the limit of the extruder motor for some samples at relatively low die temperatures (~120°C), and therefore, smaller slit heights were not considered. It was originally hoped to extrude at 80°C. However, the increase in slit height and consequent drop in pumping pressure needed to allow the motor to operate over an appropriate range of speeds would impinge on the assumption of fully developed flow necessary for data analysis.

![Figure 5.2: Schematic of slit-die showing the position of pressure transducers (dimensions are in mm, die width, W, is 25mm).](image)

Four melt pressure transducers (Dynisco, model series no. PT460) were flush mounted along the length of the die at L/H values of 10, 22.5, 35, 47.5. The transducers had
pressure ranges of 0-35 000 kPa, 0-70 000 kPa, 0-105 000 kPa and 0-105 000 kPa respectively. All transducers were calibrated at the appropriate temperatures.

Voltage signals from the transducers were recorded with a Macintosh MP100 data acquisition package. Up to ten minutes was allowed to reach steady state after changing screw speed, depending on the steadiness of the transducer signals, before recording the voltage profile over a 30 s interval. Standard deviations for the voltages gathered at the rate of 50 s⁻¹ for the period of measurement were all less than 2.5%, most below 1% of the mean voltage recorded. Extrudate samples were collected over this time interval to determine the volumetric flow rate. Enough of each sample was granulated to perform two separate runs at each temperature for each sample. One run required about 1.5 kg of sample to provide up to 6 steady state data points.

Measurements of the pressure profiles along the slit die for each of the five samples were performed at three die temperatures – 120, 140 and 160°C. The die temperatures were chosen to complement the multiple linear regression analysis required to attain temperature associated coefficients in the viscosity models presented in section 4.3. Screw speeds ranged from 5-50 rpm. The lowest possible speeds then 10, 20, 30, 40, 50 rpm were used for most samples. The upper limit was chosen after the current limit of the extruder motor was approached during experiments at 120°C. Also, higher speeds produced foamed extrudates that signified conditions conducive to a suitable plasticised thermoplastic starch were exceeded and as well, therefore, was the experimental interest at this point.

The barrel temperature profiles for slit die extrusion, listed in Table 5.1, were chosen following preliminary film blowing trials (see section 6.2).

| Table 5.1: Barrel temperature profiles for slit die experiments (°C). |
|---|---|---|---|---|
| Feed zone | Compression zone | Metering zone | Die |
| - | 130 | 130 | 120 | 120 |
| - | 130 | 130 | 130 | 140 |
| - | 130 | 130 | 140 | 160 |
5.5  **Summary of the experimental design**

The experimental study has been designed to investigate the possibility of producing a biodegradable starch plastic packaging film. The laboratory work includes process stages from selecting feedstocks, granulation, compound extrusion, through to blown film extrusion. The choice of materials for sample production maximises biodegradability of the product and minimises its cost of production. Common analytical techniques, such as DSC, GPC, tensile strength measurements and moisture absorption measurements were defined to determine some physical properties relevant to the aims of the study. A slit-die rheometry technique was defined to gather rheological data suitable for developing models of the viscous behaviour for a selection of samples. In total, the experimental design provides insight into the material flow and transformation, at the molecular level, of a polymeric material in an industrial process with a view to its ability to flow and transform in nature’s carbon cycle.
6. **Starch based biodegradable plastic packaging film:**

**Experimental results and discussion**

This chapter is divided into three sections. The first reports the process of selecting additives and extrusion conditions to improve a sample’s suitability for extruding a plastic packaging film. It includes a summary of three samples chosen to exhibit the influence of particular additives. The second section compares how these three samples performed during blown film extrusion. The third section discusses the development of models that describe viscosity as a function of shear rate and extrusion temperature for these same three samples, as well as for two re-extruded samples. The models attempt to quantify the flow behaviour that is observed during processing for the purpose of predicting final properties.

### 6.1 *Selection criteria for additives and extrusion conditions*

For a polymer to be processed into consumable plastics, a number of additives that aid in flow and produce desirable properties in the product are often extruded with the polymer. A reading of references and patents discussed in section 4.3 shows there is a significant choice of additives and their possible dosages. To limit the choices in this study, the following set of criteria were applied to choosing additives:

- Additives needed to be inexpensive and readily available;
- Additives needed to be added homogeneously through granulation, i.e. they had to be sprayable liquids, water soluble or added as a powder to dry blend with the starch (see section 5.2.2);
- There needed to be evidence of at least one of the following:
  - increase in the processing range of the sample during extrusion;
  - improvement in physical properties of the extrudate;
  - decrease in the susceptibility to moisture after extrusion; and,
- Where possible, additives should not impede biodegradability.

### 6.2 *Extruding starch with plasticisers and other additives*

Common thermoplastic additives include a group of materials known as plasticisers. Plasticisers are high boiling liquids or low melting solids that are added to polymers to modify their physical properties. Together with improving flexibility, they can modify
elongation, tensile strength, toughness, softening point, melting point, heat sealing characteristics, water absorption and other properties [327].

As discussed in chapter 4.2, the attractive forces between the amylose and amylopectin chains are hydrogen bonds and van der Waals forces. Small polar molecules can get between the chains and alter the forces holding them together, effectively behaving as plasticisers.

A number of plasticisers have been used in conjunction with starch. Plasticisation is only possible below the decomposition temperature of starch if a suitable plasticiser is added [327]. Water, being a small polar molecule, behaves as a starch plasticiser in a starch/water system.

If wanting to extrude thermoplastic starch, however, water alone is a poor plasticiser. Moisture readily diffuses to and from the extrudate with fluctuations in the temperature and humidity of the immediate environment. To help stabilize the water as a plasticiser in a thermoplastic matrix, it is combined with other plasticisers such as glycerol and other polyols that will work with water as plasticisers [294, 314].

Although other plasticisers such as xylitol and sorbitol have proven to be better starch plasticisers [294, 314], glycerol is less expensive and readily available as a by-product of other chemical processes (e.g. soap production). The efficiency of different starch plasticisers was not determined here. The practical convenience of glycerol suggested it as a suitable plasticiser for this study. Glycerol is also completely miscible in water and can be easily combined with the starch by spraying it on during granulation.

After surveying the available literature and performing trial extrusions, the amount of glycerol used for the present studies was 8.5 wt%, dry wheat starch basis. Below this, the extrudate was too brittle to consider for further processing and testing as a possible thermoplastic. Greater glycerol content increased the flexibility of the extrudate. However, any increased plasticising benefits were quickly lost [314], while the total cost of the material had increased. Therefore, a glycerol content of 8.5 wt% was held constant as part of the base thermoplastic starch for this work.
Starch with 8.5 wt% glycerol was extruded with water contents between 15 and 25 wt%. A water content of 17-19% of the total mass was observed to repeatedly produce a flexible extrudate over a greater range of processing conditions when compared to samples with higher or lower water contents. Lower water contents produced a brittle extrudate at most screw speeds. Higher water contents produced a soft extrudate that foamed with increasing screw speed. The dual nature of water in food melts has been discussed by Parker et al. [251]. Water plasticises the starch to reduce the melt viscosity and also behaves as a blowing agent to produce foam under appropriate extrusion conditions.

6.2.1 Processing conditions for compound extrusion

The extrusion temperature was required to be as high as possible to reduce the melt viscosity and to form a homogeneously mixed melt that would give the extrudate uniform thermoplastic properties. However, the amount of plasticising water that escaped the thermoplastic matrix when the extrudate foamed at melt temperatures approaching and above 100°C, it yielded a brittle and useless material in the context of this study. Consequently, temperatures were chosen to make a compromise between the two competing phenomena of plasticising and foaming.

The first heating zone was not used and the feed zone was provided with cooling water to prohibit material choking in the feed section. The next two zones were set at 120 and 100°C to promote melt mixing, then 80 and 70°C for the two zones towards the die. These temperatures produced an extrudate that was consistently well mixed and did not approach flashing temperatures for most samples. With a die temperature of 80°C the extrudate began to foam after about ten minutes of constant extrusion due to viscous heating inside the barrel. However, this did not occur with a die temperature of 70°C at similar screw speeds, and so the lower temperature was used.

The maximum speed at these temperatures that provided an extrudate capable of further processing into film was around 50 rpm. However, a screw speed of 40 rpm, corresponding to a mass flow rate of approximately 5.4 kg/hr, was used here to ensure a plasticised starch-based material that avoided excessive viscous heating and consequent flashing during extended extrusion runs. These processing conditions were assumed, through observation of extended operation, to maintain a steady-state of reactive extrusion during compounding.
Figure 6.1 shows the DSC thermograms of wheat starch and a sample extruded under the conditions described above. The samples were prepared in excess water (see section 3.3.1) to accentuate any gelatinisation peak associated with the presence of crystalline regions in the original starch granule structure. The endotherm for gelatinisation at $T_{\text{onset}} \approx 47^\circ\text{C}$ for native wheat starch disappears after the samples have been extruded, indicating an essentially amorphous, material in which the starch granules have been ‘destructurised’. Considering the low moisture content of the sample, the key reason for this would be mechanical shear forces physically disrupting the granules during extrusion [225, 321] and allowing the water molecules to penetrate starch’s crystalline structure.

![Diagram showing DSC thermograms](image)

Figure 6.1: DSC thermograms of gelatinisation peaks before and after compound extrusion.

The thermoplastic starch material obtained after the extrusion of the combination listed in Table 6.1 constitutes the base material or control case to which other samples with further additives were compared. It will be referred to as ‘Sample A’ from this point on.
Table 6.1: Sample A: Extrusion speed – 40 rpm; Die temperature - 70°C.

<table>
<thead>
<tr>
<th>Component</th>
<th>Granulation mix (g)</th>
<th>% Total mass before compounding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch</td>
<td>2000*</td>
<td>~73.5</td>
</tr>
<tr>
<td>Water</td>
<td>~730</td>
<td>17.0–19.0</td>
</tr>
<tr>
<td>Glycerol</td>
<td>200</td>
<td>~8.5</td>
</tr>
</tbody>
</table>

* Includes ~13% moisture content of the wheat starch as received.

6.2.2 Minor additives

Materials that make up less than one percent of the total sample weight are referred to as ‘minor additives’ for the purposes of this study.

The basic thermoplastic starch matrix of sample A, made of starch, water and glycerol, is very prone to the effects of moisture in the immediate environment and its variation with time. After extrusion, the extrudate quickly becomes brittle when stored at room conditions. The range of possible processing conditions is narrow as well. For example, at 50 rpm, equivalent to a mass flow rate of approximately 6.1 kg/hr, viscous heating within the extruder increased die temperatures and produced a foamed extrudate in as short a time as fifteen minutes. Obviously, such a material would be unreliable for further processing into a plastic film. Therefore, the initial part of the study was spent incorporating additives in small amounts to sample A to improve the processing range of the samples.

6.2.2.1 Trisodium trimetaphosphate (TSTMP)

Cross-linkers are used to reinforce the molecular bonds of a material. They are often used in the food industry to alter the viscous properties or to reduce solubility. Cross-linking reinforces the hydrogen bonds and van der Waals forces in the granule with chemical bonds which act as bridges between molecules [207]. TSTMP is a cross-linking agent that has been used extensively with starch in the food industry [207]. TSTMP cross-links starch by means of a covalent phosphate diester bond [328, 329] via an anionic mechanism. Figure 6.2 illustrates the proposed reaction of TSTMP with starch.

Extruding the thermoplastic starch matrix of sample A with the addition of 0.25 - 2.0 wt% TSTMP improved the flexibility of the extrudate, and increased the range of possible processing temperatures and screw speeds.
Figure 6.2: Reaction of TSTMP with starch to produce a distarch phosphate ester.

The amount of TSTMP required to cross-link sufficiently to show an effect on properties is small, only 0.01 to 3.0% based on the dry weight of starch and the reaction is promoted by increasing the pH and temperature [328]. Of course, the limit of control over molecular reorganisation during the extrusion process means that the thermoplastic matrix of the extrudate is likely to be far from an ideally organised network. Incomplete reactions yield phosphate monoesters, micro-aggregations of cross-linker, free chain ends, loops and entanglements [329].

Considering the reaction would be stifled under the relatively dry mixing conditions during granulation and the short residence time in the extruder at high temperature and pressure, the pH of the solution used for granulating the samples was raised to 10 - 10.5 by adding a small amount of sodium hydroxide (NaOH). Kulicke et al. [329], when studying starch hydrogels, reported that NaOH increased the hydrolysis of the diester phosphate linkage and brought about the disintegration of some elastically effective entanglement points. In the food industry, distarch phosphates have exhibited substantial thermal stability (see Table 6.2), a property that effectively increases the processing ranges for extrusion by containing the effects of viscous heating.
TSTMP is also water-soluble. As such, 0.25 wt% TSTMP was added to sample A as part of ‘sample B’, by spraying an aqueous solution with a pH of 10-10.5 on the starch during granulation to improve the stability of the thermoplastic starch structure during processing.

6.2.2.2 Methyl(triethoxy)silane

Although TSTMP helps to improve the processing ranges of Sample A, it does not slow the movement of water to and from the plastic, and in fact can increase water activity via the anionic character associated with the starch phosphate diester cross-links [329]. A novel approach to slow the passage of water to and from the plastic was to include an organosilane as an additive. Organosilanes are used as starting materials for the production of organosiloxanes. Organosiloxanes are polymeric and possess the typical structural features of organic macromolecules. They hold an intermediate position between the organic and inorganic compounds, particularly between silicates and organic polymers [330]. Organosiloxane materials have demonstrated properties such as biocompatibility, thermal and UV stability, low glass transition temperatures and hydrophobic surfaces [331].

The organosilane chosen for this study was methyl(triethoxy)silane. (It was chosen primarily because it was readily available). It has the chemical structure shown in Figure 6.3.

![Structure of methyl(triethoxy)silane](image)

Figure 6.3: Structure of methyl(triethoxy)silane.

Methyl(triethoxy)silane is listed by Cole and Daumesnil [306] as a possible organosilane additive to modify the surface properties of proposed starch/zein polymeric materials and to increase the water-repellency of the starch molecule. As little as one molecule to 1000 anhydroglucose units of starch can show a visible effect.

With limited knowledge of the possible interactions of methyl(triethoxy)silane with starch, 0.5 wt% of the organosilane (a liquid) was sprayed onto the starch during granulation with
the aim to increase the hydrophobic properties of the thermoplastic starch material by creating a barrier to the movement of water molecules, particularly near the surface.

Methyl(triethoxy)silane and TSTMP at a pH of 10-10.5 were therefore added to sample A to enhance its processing range. This second combination of materials is referred to as sample B.

6.2.2.3 Succinic Anhydride
Succinic anhydride is a white crystalline powder that can be derived from amber, lignite or other plant sources. It can also be synthetically produced during alcoholic fermentation. Caldwell [332] found that granular starch treated with substituted cyclic dicarboxylic acid anhydrides increased the ease of flow of granules in the dry state, and the starch was more resistant to wetting with water. The reaction of starch with succinic anhydride usually forms the half-ester shown in Figure 6.4. Side reactions include hydrolysis reactions, cross-linking, (by forming a di-ester), and complex formation [333, 334].

![Figure 6.4: Reaction of succinic anhydride with starch to produce the acid-ester.](image)

Succinic anhydride was dry blended with starch during granulation. Addition of 0.25-0.5 wt% succinic anhydride to starch provided clear evidence of improved plastic properties during extrusion. The extrudate was white, flexible at room conditions, avoided foaming at conditions that produced foaming in sample A. However, further processing of materials with 0.5 wt% succinic anhydride tended to produce a foamed and brittle extrudate unable to be blown into film. Therefore, samples were prepared similarly to sample B, but with the addition of 0.25 wt% of succinic anhydride to constitute ‘sample C’.

6.2.3 Summary of initial observations for samples A, B and C
Table 6.2 shows the level of additives for each of the three samples. The approximate values for starch and glycerol are used because of the allowable variation in moisture
content. The values of the other additives were worked out on a starch basis rather than of the total sample.

Table 6.2: Level of additives for each sample before compound extrusion.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Starch (wt% total)</th>
<th>Glycerol (wt% total)</th>
<th>TSTMP (wt% starch basis)</th>
<th>Methyl(triethoxy)silane (wt% starch basis)</th>
<th>Succinic anhydride (wt% starch basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>~ 73.5</td>
<td>~8.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>~ 73.0</td>
<td>~8.5</td>
<td>0.25</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>~ 73.0</td>
<td>~8.5</td>
<td>0.25</td>
<td>0.5</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*Sample A* provides the base case for the study. The starch polymers, amylose and amylopectin, were plasticised with the most inexpensive and readily available plasticisers that have been used in the literature. Sample A repeatedly produced good extrudate that appeared homogeneously mixed and flexible at the compounding conditions described in section 5.2.3. However, the sample was susceptible to the effects of viscous heating that lead to foaming during extrusion trials lasting more than fifteen minutes. Also, the plasticisers were not inclined to stay in the thermoplastic matrix. Hence, this thermoplastic starch sample quickly becomes brittle and difficult to handle and its processing potential quickly deteriorates. Sample A can be regarded as the worst case scenario for the study.

*Sample B* was designed to improve the range of processing conditions of the thermoplastic starch material and to also improve its barrier properties. Cross-linking with TSTMP improves the continuity of the matrix through chemical bridging between the natural polymers, and as such helps retain the flexibility and plasticity of the thermoplastic starch, as well as improving the thermal stability of the material during processing. Methyl(triethoxy)silane helps impede the movement of the plasticising molecules to and from the thermoplastic matrix near its surface by promoting the formation of an organosiloxane network at the surface.

*Sample C* was included to compare a thermoplastic starch in which the polymers have been chemically altered with a cyclic dicarboxylic acid anhydride to produce ester groups that are likely to induce different flow behaviours. Extrudates of sample C were consistently smooth and white. The extrudate was very flexible and easy to handle for further processing and testing. After initial observations, sample C has the greatest processing potential of all the samples. The literature also suggests improvement in water absorption properties when starch succinates are formed [332, 333].
The moisture content of the compounded extrudates was 2.5 – 3.5% lower than that of the sample before extrusion. This decrease is due to a combination of water evaporation at the die exit and loss of water to chemical reactions and other molecular interactions that occur during extrusion. Table 6.3 provides an idea of the control over sample moisture contents before and after extrusion for a single set of experiments.

Table 6.3: Sample moisture contents for a single set of experiments (wt% of total sample).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Before compound extrusion</th>
<th>After compound extrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>17.93 ± 0.06</td>
<td>14.51 ± 0.15</td>
</tr>
<tr>
<td>B</td>
<td>18.51 ± 0.29</td>
<td>15.48 ± 0.31</td>
</tr>
<tr>
<td>C</td>
<td>18.14 ± 0.11</td>
<td>15.65 ± 0.24</td>
</tr>
</tbody>
</table>

Controlling the moisture content of the samples to a greater degree was difficult because of the method of granulation used. Changes in humidity and temperature in the immediate environment meant that drying times for granulation changed slightly depending on the weather. However, no samples with a moisture content before compounding of less than 17 wt% or greater than 19 wt%, were used. This range was assumed to be acceptable for a meaningful comparison of the viscous properties of the different samples.

Figure 6.5 displays the rate of water absorption for samples immersed in water over a period of twenty-four hours (see section 5.3.3 for method). To illustrate the effect of TSTMP with water one more sample other than A, B, and C was included here – sample A + 0.25 wt% TSTMP.
Figure 6.5: Moisture absorbed over a twenty-four hour period by samples when immersed in water.

It is observed from the data up to 120 minutes for sample B and the altered sample A that TSTMP does indeed increase water absorption compared to sample A. This effect agrees with the literature [329]. TSTMP then, may improve the processing properties of thermoplastic starch, but it doesn’t assist in improving barrier properties. However, if the data for sample B and the altered sample A are compared, there is less moisture absorbed for that sample containing methyl(triethoxy)silane, that is, sample B. The orgnosiloxane improves barrier properties as expected, but not to the extent of counteracting the effects of TSTMP. The data for sample C up to the 120 minute mark suggest that the addition of succinic anhydride markedly improves barrier properties, as determined here from the amount of moisture absorbed. This hydrophobic effect has been commented upon in the literature [332, 333]. As time proceeds though, the difference between the samples reduces, suggesting that any differences due to additives are not permanent in a moist environment.

This loss of difference between sample properties seems to be supported by the tensile property data presented in Table 6.4 (see section 5.3.4 for method). Initially, sample C appears to be more flexible (higher strain at break). But all samples soon become quite brittle, exhibiting similar values for strain at break after two and four days of storage. However, the most significant fact coming from the tensile data is the lack of repeatability between test specimens when measuring Young’s modulus (measured at 1% of strain at
break). Sample B on day 0 shows some repeatability with a standard deviation less than 10% of the average value. This illustrates a key problem with a material that relies solely on native starch for providing the thermoplastic matrix. Material properties are inconsistent and this is a good reason why starch is more commonly combined with other polymers.

Table 6.4: Tensile properties measured for samples.

<table>
<thead>
<tr>
<th>Days storage</th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Strain at break (%)</td>
<td>Youngs modulus 1% (Mpa)</td>
<td>Strain at break (%)</td>
</tr>
<tr>
<td></td>
<td>68.97 ± 18.39</td>
<td>57.98 ± 28.97</td>
<td>60.35 ± 18.27</td>
</tr>
<tr>
<td>2</td>
<td>11.80 ± 2.59</td>
<td>104.46 ± 73.97</td>
<td>9.96 ± 1.72</td>
</tr>
<tr>
<td>4</td>
<td>10.33 ± 3.88</td>
<td>80.84 ± 69.80</td>
<td>11.17 ± 2.53</td>
</tr>
</tbody>
</table>

### 6.3 Blown film extrusion

Samples were extruded through an annular film blowing die as described in section 5.2.4. A process of trial and error was used to find a range of screw speeds and temperature profiles for the extruder barrel and die suitable for extruding a thermoplastic starch film. It was found that extruder barrel and film die temperatures needed to be at least 100°C, preferably 110 or 115°C and screw speeds at least 50 rpm, preferably 60 or 70 rpm for the material to be extruded through the die. Higher temperatures and faster screw speeds were needed to decrease the viscosity of the material for it to overcome the greater pressure of extruding through the film die. But just as higher temperatures and faster screw speeds caused the extrudate to foam during compound extrusion, so they did during blown film extrusion. Therefore, 110°C and 60 rpm were used for most runs where data on a film-like extrudate could be gathered.

Ideally, it would be most cost effective if the samples could be fed to the extruder in granular form, the materials compounded and reacted and a plastic film extruded in a single step. It was found, though, that no samples fed to the extruder in granular form were able to produce a film at the conditions mentioned above. All samples foamed easily at the die exit and were incapable of forming a bubble.

Samples were then fed to the extruder in compounded pellet form, i.e. after they had been extruded once. Sample A extruded in this form was again unable to form a bubble, with
the extrudate often foaming, having a rough, inconsistent surface and breaking easily when handled.

However, samples B and C extruded in pellet form were at least able to form a continuous bubble. It appeared that the loss of about 3% moisture (see Table 6.3) during compound extrusion and the extent of reactions that took place then were changes enough to allow the material to be processed at higher temperatures and faster screw speeds. At a die temperature of 120°C and a screw speed of 80 rpm though, the material foamed at the die exit after a short time of extrusion. Table 6.5 summarises what data could be obtained for the samples at different operating conditions.

Table 6.5: Summary of observations for samples A, B and C.

<table>
<thead>
<tr>
<th></th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die temperature range</td>
<td>90, 100, 110, 120</td>
<td>90, 100, 110, 115, 120 (preferably 110)</td>
<td>90, 100, 110, 115, 120 (preferably 110)</td>
</tr>
<tr>
<td>Screw speed range (rpm)</td>
<td>50 - 80</td>
<td>50-80, preferably 60</td>
<td>50-80, preferably 60</td>
</tr>
<tr>
<td>Maximum BUR</td>
<td>-</td>
<td>2.1-2.3</td>
<td>2.1-2.3</td>
</tr>
<tr>
<td>Minimum film thickness (mm)</td>
<td>&gt;1 mm at die exit</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Stability comments</td>
<td>-</td>
<td>Slow rate of extrusion allowed bubble to eventually return to stable after disturbances in bubble pressure. Range of processing conditions too narrow for meaningful stability study.</td>
<td></td>
</tr>
<tr>
<td>General comments</td>
<td>Unable to extrude workable bubble from either granules or compounded pellets. Easily foamed. Thick, severe shark-skinning, extruded film stuck together.</td>
<td>Unable to extrude in granules. However, re-extruded pellets were able to form bubble. Extrusion rate slow and little ability to stretch in axial direction. Film sometimes blocked at nip rolls for thicker film.</td>
<td>Unable to extrude in granules. However, re-extruded pellets were able to form bubble. Extrusion rate slow and little ability to stretch in axial direction. Bubble had a smoother surface than sample B. No blocking of film.</td>
</tr>
</tbody>
</table>

Bubbles able to be formed with re-extruded samples B and C could be drawn in the ‘hoop’ or circumferential direction (BUR increased) by increasing the air pressure inside the bubble. In fact, the maximum BUR achieved with the samples here of 2.5 is comparable to the lower ranges of BUR used to extrude petrochemical polymer films [173-175]. Stretching the bubble in the axial direction, on the other hand (increasing TUR) was almost
impossible. The nip rolls at the top of the rig were generally used to draw the bubble upwards at a velocity only slightly greater than the material left the die.

This inability to stretch the starch material is most likely due to the size of the starch polymers. The native wheat starch used here is about 30% amylose (molecular weight 100 000 – 1 000 000) and 70% amylopectin (molecular weight can be several million). Petrochemical polymers usually have molecular weights no greater than 100 000. With such large molecules, it is unlikely the material will be subject to great rates of deformation. Where starch films have been produced, it is usually high amylose starch that is used [335]. More recent work by Thunwall et al. [315] found a similar problem during film blowing when using native potato starch. It was far more difficult to process than the hydroxypropylated potato starch used for comparison. However, the urea/formamide used to plasticise high amylose TPS by Zullo and Iannace [318] was able to produce a homogenous film as thin as 50 μm.

It is immediately apparent that such a starch-based material is incapable of producing a decent thermoplastic film. High density polyethylene (HDPE) film can easily achieve thicknesses of 0.01 mm at bubble pressures far lower than those used here [173, 174]. It was originally hoped that the extrusion process could be filmed and deformation rates be calculated stability regions identified at different operating conditions to compare to previous results for petrochemical polymers [162, 173-175, 179, 201, 202]. However, obtaining meaningful data from the video was very difficult. Extrusion rates were slow, the outline of the bubble was unsteady and there appeared to be no definite freeze line when temperatures were read with an infra-red pyrometer. This lack of a definite freeze line is the result of the thickness of the film, as well as the complex morphology of the material. The extruded film is likely to be a combination of gelled, melted or partially converted starch material [221].

Figure 6.6 shows an example of what the bubble looked like for re-extruded sample C. Although there was little difference between the properties of samples B and C, sample C produced a smoother bubble that was less prone to blocking at the nip rolls. The inability of the material to stretch in the axial direction is also noticed by the manner in which the bubble expands in the circumferential direction just above the die exit. This is a notable difference between the extruded starch material and what is observed during blown film extrusion of conventional plastics that draw far more easily in the axial direction to create
more of a wine glass shape [183, 186, 193]. However sample C performed better in this respect compared to sample B. This observation is supported by the tensile test results in Table 6.4. Before storage, sample C produced an average strain at break of 110% compared with mean values of 69% for sample A and 60% for sample B.

Figure 6.6: Video frame of blown film extrusion of re-extruded sample C, sample Cx.

6.4 Viscosity models

Following the initial trials of compound extrusion and blown film extrusion, it was decided to measure the viscosity of the samples at different temperatures and screw speeds in order to help quantify some of the effects that were observed. Five samples were studied – samples A, B and C, and two further samples Bx and Cx. Samples Bx and Cx are re-extruded (pelletised) samples of B and C and were included because of their better performances during blown film extrusion. Section 5.4 describes the slit-die fitted with pressure transducers used to gather the data.

6.4.1 Analysis of data

Initially, viscosity was determined as a function of shear rate using the power law model common in describing the pseudoplastic behaviour of non-Newtonian fluids. The shear rate produced within the die was altered through a change in screw speed. The screw was flood fed keeping the volume per screw turn of material being fed to the extruder barrel constant. Consequently, each screw speed conceived a thermo-plastic starch material that had undergone a different degree of thermo-mechanical treatment in the barrel to that produced at another screw speed.
Some researchers have attempted to control the amount of thermo-mechanical treatment prior to viscosity measurements in an attempt to acquire data for the one rheological fluid at various shear rates [248, 261]. However, controlling the amount of feed into the single screw extruder at constant screw speed as a means of separating the time of thermo-mechanical treatment and shear rate was not possible to any degree of control with the apparatus used in this study. Strictly speaking then, the fact that the data is gathered at different screw speeds means that it reflects the flow properties of several rheological fluids for a single thermoplastic starch sample, each differing by the extent of starch conversion and fragmentation induced during extrusion. However, the differences in starch conversion and fragmentation over the range of screw speeds used here for any single sample are initially assumed small enough to be able treat the data as that for a single rheological fluid.

The analysis of the data follows that for a power law fluid as described in Han [336]. The shear stress at the wall, $\tau_w$, and apparent shear rate, $\dot{\gamma}_a$, were calculated using

$$\tau_w = -\frac{H}{2} \frac{dP}{dz}$$  \hspace{1cm} (6.1)$$

$$\dot{\gamma}_a = \frac{6Q}{WH^2}$$  \hspace{1cm} (6.2)$$

respectively. The axis of flow along the length of the slit is denoted the z-direction. $P$ is the pressure at any point along the slit surface due to the normal force of the fluid flowing through the slit. A linear pressure gradient was assumed for $dP/dz$ in using Eq. 6.1. Further details of its calculation are provided in the following section. To calculate the volumetric flow rate, $Q$, the density of the melt was assumed to be 1.4 g/cm$^3$. Similar values have been reported for the density of starch based materials (1.2 – 1.5 g/cm$^3$ [245, 247, 252, 261]). Within this range, the sensitivity of the calculated model parameters to density values is negligible.

The shear rate at the wall, $\dot{\gamma}_w$, can be found by applying the Weissenberg-Rabinowitsch correction:
\[ \dot{\gamma}_w = \dot{\gamma}_a \left( \frac{2n + 1}{3n} \right) \]  

(6.3)

where \( n \) is the flow index, calculated from the slope of shear stress, \( \tau_w \), against apparent shear rate, \( \dot{\gamma}_a \), on a log-log scale. The true viscosity is found with Eq. 6.4.

\[ \eta_t = \frac{\tau_w}{\dot{\gamma}_w} \]  

(6.4)

Viscosity as a function of shear rate is expressed in the power law form as

\[ \eta_t = K \left( \dot{\gamma}_w \right)^{n-1} \]  

(6.5)

where \( K \) is a constant referred to as the consistency index.

### 6.4.2 Results and discussion of the power law fluid model for viscosity

#### 6.4.2.1 Calculated results

Power law constants for each of the samples are provided in Table 6.6. The values for each of the two runs as well as values obtained through combining all the data for each sample are given. Table 6.6 shows that the correlations between Eq. 6.5 and the experimental slit die data is statistically significant to a high degree for most cases (\( R^2 > 0.98 \)). In four cases the regression coefficient, \( R^2 \), is less than 0.95. The regression coefficient for individual runs represents the significance of the data points to each other within each run, whereas that for combining data also includes a measure of repeatability between the runs. Generally, the regression coefficient for the combined data of each sample is lower than that for either of the respective individual runs.

Figures 6.7 – 6.10 show the dependence of viscosity on shear rate. Viscosity decreases with shear rate in all cases, indicative of typical shear thinning behaviour. These figures readily show that temperature greatly affects the appearance of the data. The organised correlations apparent at 120°C lose definition as the range of experimental shear rates obtained for each of the samples decreases at higher temperatures.
Table 6.6: Power law constants for all slit-die experiments.

<table>
<thead>
<tr>
<th>Sample - Temp. (°C)</th>
<th>Flow index, n</th>
<th>Consistency index, K (Pa.sⁿ)</th>
<th>Regression coeff., R²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run 1</td>
<td>Run 2</td>
<td>Combined</td>
</tr>
<tr>
<td>A – 120</td>
<td>0.05</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>A – 140</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>A – 160</td>
<td>0.30</td>
<td>0.27</td>
<td>0.29</td>
</tr>
<tr>
<td>B – 120</td>
<td>0.11</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>B – 140</td>
<td>0.17</td>
<td>0.16</td>
<td>0.17</td>
</tr>
<tr>
<td>B – 160</td>
<td>0.26</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>Bx – 120</td>
<td>0.28</td>
<td>0.27</td>
<td>0.31</td>
</tr>
<tr>
<td>Bx – 140</td>
<td>0.33</td>
<td>0.24</td>
<td>0.29</td>
</tr>
<tr>
<td>Bx – 160</td>
<td>0.45</td>
<td>0.42</td>
<td>0.43</td>
</tr>
<tr>
<td>C – 120</td>
<td>0.14</td>
<td>0.15</td>
<td>0.16</td>
</tr>
<tr>
<td>C – 140</td>
<td>0.34</td>
<td>0.33</td>
<td>0.34</td>
</tr>
<tr>
<td>C – 160</td>
<td>0.56</td>
<td>0.70</td>
<td>0.61</td>
</tr>
<tr>
<td>Cx – 120</td>
<td>0.31</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>Cx – 140</td>
<td>0.47</td>
<td>0.30</td>
<td>0.40</td>
</tr>
<tr>
<td>Cx – 160</td>
<td>0.51</td>
<td>0.60</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Figure 6.11 provides examples of the typical pressure profiles obtained along the slit-die. The profiles were predominantly linear in nearly all cases as assumed in equation 6.1 for deriving the relationships depicted in Figures 6.7 – 6.10. The pressure profiles transmitted by the three transducers at L/H values of 22.5, 35, and 47.5, that is, those closest to the end of the extruder were used to calculate dP/dz. Theoretically, any slope between any points should be equal and therefore any combination of points can be used in the analysis. However, the validity of assuming any profile whether it is linear, quadratic, or otherwise is still debatable [337, 338]. Obvious deviations from the linear profile near the die exit, particularly at 120°C, led to the data at L/H=10 being neglected throughout the analysis. This should have little consequence in distorting any conclusions ensuing, as the pressures transmitted closer to where the slit die is attached to the extruder barrel best reflect the changes associated with the extrusion process rather than any changes that might occur through the slit die.
Figure 6.7: Viscosity vs shear rate at 120°C for all samples.

Figure 6.8: Viscosity vs shear rate at 140°C for all samples.
Figure 6.9: Viscosity vs shear rate at 160°C for all samples.

Figure 6.10: Viscosity vs shear rate for all samples at specified die temperature.
Figures 6.12 – 6.14 show the change of shear stress with speed. Lines are included with the data points here as a guide for the reader. Figures 6.15 – 6.17 show similar trends of shear stress with apparent shear rate. Remembering that shear rate was altered through a change in screw speed, it is clear from Figures 6.12 – 6.17 that common speeds develop different apparent shear rates in the slit die for different samples because of their differing viscosities.

To calculate the flow index, n, for samples A, B and C at 120°C via \( \frac{d\ln \tau_w}{d\ln \dot{\gamma}_a} \), the points providing a positive slope in Figure 6.15 were used where the slope of a single curve changed conspicuously from positive to negative. Reasons for this will become clear in the following discussion. In some cases, data gathered at speeds of less than 10rpm were ignored due to large deviations from the data trend. These large deviations could be due to the inadequacy of the power law model to hold at low shear rates [180], be associated with a property of the material, or because of the lack of control over the extruder motor at low speeds. In most cases, particularly at the higher temperatures, all data fitted a linear profile of \( \frac{d\ln \tau_w}{d\ln \dot{\gamma}_a} \) to give a reliable value of the flow index, n. The

Figure 6.11: Typical pressure gradients along the slit die (data for Sample A).
wall shear rate, $\dot{\gamma}_w$, was calculated with Eq. 6.3 for all data points in the run using the appropriate value of $n$ to provide the relationships shown in Figures 6.7 – 6.10.

Figure 6.12: Shear stress vs speed at 120°C.

Figure 6.13: Shear stress vs speed at 140°C.
Figure 6.14: Shear stress vs speed at 160°C.

Figure 6.15: Shear stress vs apparent shear rate at 120°C.
Figure 6.16: Shear stress vs apparent shear rate at 140°C.

Figure 6.17: Shear stress vs apparent shear rate at 160°C.
6.4.2.2 *The effects of mechanical shear*

The flow index, $n$, reflects the extent to which the viscosity of the extrudate depends on shear rate. Comparison of the sample’s flow curves and their respective flow indices can imply the extent to which mechanical shear modifies the flow properties of the extruded thermoplastic starches, in relation to competing starch conversion influences such as temperature and processing additives. Generally for thermoplastics, $0 < n < 1$, where $n \sim 0$ represents severe shear-thinning behaviour, (shear forces dominate how the material flows), and $n \sim 1$ represents Newtonian flow behaviour, or flow that is independent of the effects of shear.

Referring to Table 6.6, $0.05 \leq n \leq 0.70$ for the samples investigated in these experiments. Similarly, the literature contains a large range of values for $n$, calculated for several starch-based materials extruded at various processing conditions. Padmanabhan and Bhattacharya [245] reported $-0.298 \leq n \leq 0.967$ for corn meal extruded with a single screw extruder, over a temperature range of 150-180°C and moisture contents of 25-45%. van Lengerich [222] reported $n > 1$, indicative of shear-thickening behaviour, for wheat starch extruded with a twin screw extruder at moisture contents of 40% and/or a barrel temperature of 200°C. Xie et al. [320] reported values for $n$ between 0.03 and 0.85 within a series of corn starches of differing amylose/amyllopectin ratios processed with water. It has commonly been shown throughout the literature for starch-based food materials that increasing the moisture content and temperature at constant screw speed (or shear rate) increases the flow index, $n$ [222, 231, 245-251, 320].

Thermoplastic starch and starch/poly(ethylene-co-vinyl alcohol) blends prepared by Villar et al. [290] produced flow indices $0.119 \leq n \leq 0.643$. Several additives have been reported to yield flow indices of $0.39 \leq n \leq 0.67$ for thermoplastic starch materials [321]. As was found with starch-based food materials, the flow index increased with moisture content (which can be incorporated into and regarded as the level of plasticiser), temperature, and level of plasticiser in the starch-based thermoplastic [321]. Shear rate dependence of the blends studied by Villar et al. [290] increased (i.e. $n$ decreased) with increasing amylose content, explained by the likelihood of the linear amylose molecules to become more entangled under shear [242]. For comparison, a PS at 150°C has a flow index of 0.4 [339] and LDPE at 200°C has a flow index of 0.398 [249].
Samples A, B and C all exhibit low values for $n$, 0.05-0.16 at 120°C (Table 6.8). Low values of $n$ and $n \leq 0$ are indicative of severe shear-thinning behaviour. Possible explanations of such behaviour for polymeric materials are *molecular degradation (fragmentation), pressure dependence of viscosity, viscous dissipation, slip and yield stress* [245].

Figures 6.12 and 6.15 illustrate an interesting transition in samples A, B and C produced at screw speeds between 15-20 rpm. The slope of the graph changes from positive to negative. This is a clear indication of *molecular degradation*. The short residence times in the extruder keep any significant thermal degradation from occurring, and therefore degradation will substantially be the result of mechanical shear effects. The actual mechanisms of degradation will in fact be a combination of shear, moisture and temperature effects [245]. Such degradation leads not only to changes in molecular weight and molecular weight distribution, but also structural changes of the molecules. Molecular parameters are primarily responsible for the behaviour of the material during processing, and therefore fragmentation warrants particular interest, remembering also that extrusion of the thermoplastic starch samples in this study involves a number of chemical reactions that are functions of the molecular structure at any instant during extrusion.

A number of publications note the effect of low moisture content on the molecular degradation of starch during extrusion [224, 228, 233, 236, 257, 261]. The influence of moisture content on viscosity has been modelled with significant success using an exponential relationship with viscosity, first by Harper et al. [254] (Eq. 3.10). Moisture content in this study, however, is maintained at a level of ~18.0 wt% of the total weight of granulated samples and is regarded as an integral part of the extruded starch-based thermoplastic. Explaining the effects of glycerol and water as a combined plasticiser in the thermoplastic starch matrix suggests this approach. The average moisture contents of the samples used here are provided in Table 6.7.
Table 6.7: Initial moisture contents of slit extrusion samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Moisture Content (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run 1</td>
</tr>
<tr>
<td>A</td>
<td>17.77 ± 0.18</td>
</tr>
<tr>
<td>B</td>
<td>18.10 ± 0.14</td>
</tr>
<tr>
<td>Bx</td>
<td>13.84 ± 0.53</td>
</tr>
<tr>
<td>C</td>
<td>17.16 ± 0.09</td>
</tr>
<tr>
<td>Cx</td>
<td>12.68 ± 0.52</td>
</tr>
</tbody>
</table>

The low moisture contents listed in Table 6.7 suggest molecular fragmentation is likely to occur for all samples, particularly at low temperatures. Fragmentation of the starch molecules would be primarily responsible for the severe shear-thinning behaviour observed at 120°C for Samples A, B and C in Figure 6.15. Further evidence is provided by the fact that the compounded samples Bx and Cx show no such dramatic change in slope, despite having significantly lower moisture contents. However, sample Bx is likely to be exhibiting a similar phenomenon to a lesser extent in Figure 6.15. Also, Figure 6.12 shows a change in the accumulation of shear stress at around 25 rpm for samples Bx and Cx compared to less than 20 rpm before a noticeable transition in samples A, B and C. Any mechanisms responsible for modifications in these granular samples, which essentially contain starch in the native granular state, still occur with subsequent extrusions, but to a far lesser degree.

Figure 6.18 provides evidence of the fragmentation of the starch molecules during extrusion. It shows the GPC elution curves for native starch and a number of extruded samples. Starch is expected to generate two peaks in the elution curve during GPC [340, 341]. The first peak is attributed to the larger amylopectin fraction and the smaller amylose molecules of starch form the second. However, the size of the amylopectin molecules often excludes them from the chromatographic column to some degree.

In Figure 6.18, the only peak present for native starch appears to represent the amylose fraction. Spreading of the possible amylose peak, as seen for sample B, suggests possible molecular conglomerates of size between that of amylose and amylopectin as a result of granulating starch with sample additives. TSTMP has been shown to react and form bridging cross-links within starch in a dry state at elevated pH [328]. The possible formation of organosiloxane network with the starch molecules may also produce
molecular conglomerates of intermediate size that are not destroyed when dissolved in DMSO.

Figure 6.18: Elution profiles for GPC analysis of sample B extruded once (Bx-1) and twice (Bx-2) at compounding conditions.

Successive extrusions (at compounding conditions in this case) induce molecular size changes within the thermoplastic starch material most prominent after initial destructuring of the starch granules, becoming less significant with each pass through the extruder, in spite of the reduction in moisture content for the re-extruded samples (see Table 6.7). The fraction of material in the intermediate molecular size range relative to raw wheat starch increases. According to Rodis et al. [235], only a small fraction of the total glycosidic bonds can expect to be affected by extrusion. Their analyses suggest cleavage could occur within the inter-cluster regions of the amylopectin molecule, rather than adjacent to the reducing or non-reducing termini. Debranching of amylopectin has been identified as a mechanism of fragmentation [236, 238] and helps explain the transformation of the elution curves in Figure 6.18. Although it is not possible to dissociate the factors responsible for the appearance of severe shear-thinning behaviour, molecular degradation through mechanical shear does appear to dominate the flow behaviour of granular samples at 120°C, producing low values for the flow indices.
The physical reduction in molecular size during compounding would be expected to induce even greater severe shear-thinning behaviour than that observed in Figure 6.15 because of the lower extrusion temperatures. Therefore, the reduced effect of mechanical shear during subsequent extrusions would explain the consistently higher flow index values and lower stresses measured for samples Bx and Cx compared to their respective granular samples, despite the lower levels of plasticiser.

The dramatic changes exhibited in Figures 6.12 and 6.15 by samples A, B and C at 120°C could be considered as representative of an energy level required for the significant changes in starch molecular structure [245] that are observed in Figure 6.18. The corresponding shear stresses at these transitions could also be regarded as characteristic molecular *yield stresses* of the thermoplastic starch samples. Viscosity calculations for samples A, B and C at 120°C assume a constant positive value of n and therefore reflect the viscosity of materials that have *not* undergone significant fragmentation. Calculation of viscosity using a negative flow index value after the point of transition can lead to negative viscosities, a meaningless result. Therefore, a term to incorporate fragmentation contributions to viscosity after the so called yield stress of the molecules has been exceeded is necessary for a more correct interpretation of the viscous flow behaviour of these thermoplastic starch samples at low temperatures.

The *pressure effects of viscosity* could not be practically determined for the samples in this study. Changes in flow behaviour due to pressure effects would likely become increasingly important when the extrudate tends to foam at higher temperatures and screw speeds, as the volatility of the plasticisers increases.

*Viscous dissipation* can cause the temperature along the length of the die to increase and result in shear-thinning like behaviour of the flow curve. It was not possible to probe the melt temperature along the die. However, Padmanabhan and Bhattacharya [245] theoretically calculated the temperature rises expected for corn meal extruded through a slit die and concluded that any such rises would be insignificant in changing n, compared to the effects of molecular degradation.

Plug flow in the die can produce a severe shear-thinning curve that can be interpreted as *slip* [342]. Mooney [343] devised a convenient method of determining the presence of slip
by comparing sample flow curves obtained using different capillary diameters or slit heights. However, the change in die dimensions would affect the extent of starch conversion during extrusion for a given screw speed or shear rate and the problem of measuring rheologically different fluids arises. Molecular modifications must be corrected for before the Mooney method can be applied to check for the presence of slip [245].

6.4.2.3 The effect of temperature

As the temperature increases, \( n \) increases for each of the samples suggesting the influence of mechanical shear, (and therefore fragmentation), on the flow properties decreases. Figures 6.16 and 6.17 show essentially linear responses of shear stress with shear rate for all samples at 140 and 160°C respectively, implying fragmentation reactions lose influence as temperature associated phenomena gain it.

The consistency coefficient, \( K \), (in Eq. 6.5), has been found to follow an Arrhenius relationship with temperature for polymer melts (Eq. 6.6):

\[
K = K' e^{(E_a/RT)}
\]  

(6.6)

Here, \( K' \) (Pa\cdot s^n) is a new empirical constant, \( E_a \) is the activation energy (J/mol), \( R \) the ideal gas constant (J/K mol) and \( T \), the temperature (K).

The range of consistency index for the samples here, \(~6000 \leq K \leq ~150000\) Pa\cdot s^n, is comparable to that found in the literature for a number of extruded starch materials. The thermoplastic starch blends studied by Villar et al. [290] produced a similar range of \(~3130 \leq K \leq 238000\) Pa\cdot s^n, increasing with the amylose content of the blends. It was also noted that the consistency index is more sensitive than the flow index to humidity fluctuations of the storage environment. Increasing the moisture content (and therefore plasticiser level) and temperature have been shown repeatedly to decrease consistency index, \( K \), for many starch-based materials [222, 245, 248, 249, 251, 252, 291, 321]. van Lengerich [222] reported a value of 5841 Pa\cdot s^n for wheat starch with 25% moisture content extruded at 170°C, decreasing to 35 Pa\cdot s^n for wheat starch with 40% moisture content. Tanner [339] listed a consistency index, \( K \) of 160000 Pa\cdot s^n for polystyrene at 150°C and Senouci and Smith [249] found a value of 9700 Pa\cdot s^n for LDPE extruded at 200°C.
Referring to Table 6.6, samples A, B and C extruded at 120°C are all at the upper end of the range of values calculated in this analysis and samples C and Cx extruded at 160°C are at the lower end, suggesting that temperature, the additives and molecular weight distribution all interact to significantly influence flow behaviour of the thermoplastic starch samples.

Figure 6.19 illustrates the linear relationships observed between consistency index, K, and the inverse of absolute temperature, 1/T, that constitute an Arrhenius relationship between viscosity and temperature for each sample. The lines in Figure 6.19 are a best fit representation.

![Consistency index, K (Pa·s), vs. inverse of absolute temperature, 1/T, for each sample.](image)

Incorporating Eq. 6.6 into Eq. 6.5 gives a new expression for the calculation of the viscosity, \( \eta \), that includes temperature.

\[
\eta = K' (\dot{\gamma})^{m-1} e^{(E_a/RT)}
\]  

(6.7)

Here, \( m \) is used as the constant associated with shear. It is similar to the flow index, \( n \), in Eq. 6.5 but is instead considered unchanging with temperature, in contrast to \( n \).
represents a fixed flow index for the material being extruded at any temperature and is dimensionless.

Such an expression for starch-based materials was first used by Harper et al. [254] to calculate the viscosity of extruded cooked cereal doughs. An exponential term accounting for the effects of moisture content was also included (see Eq. 3.10). However, no such term is considered here. In this study, the moisture content was held constant and regarded as an integral part of the thermoplastic starch being extruded.

Taking the natural logarithm of each side of Eq. 6.7,

$$\ln \eta = \ln K' + (m - 1) \ln \dot{\gamma} + \frac{(E_a/R)}{T}$$

(6.8)

The constants $K'$, $m$, and $(E_a/R)$ were determined empirically through multiple linear regression of the viscosity versus shear rate data at 120, 140 and 160°C. Table 6.8 lists the constants obtained for each of the samples with their respective regression coefficients.

Table 6.8: Constants for viscosity model (Eq. 6.8).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$K'$ (Pa.s$^n$)</th>
<th>$m$</th>
<th>$E_a/R$ (K)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>175</td>
<td>0.17</td>
<td>2370</td>
<td>0.976</td>
</tr>
<tr>
<td>B</td>
<td>27.6</td>
<td>0.16</td>
<td>3220</td>
<td>0.972</td>
</tr>
<tr>
<td>Bx</td>
<td>19.1</td>
<td>0.34</td>
<td>3010</td>
<td>0.957</td>
</tr>
<tr>
<td>C</td>
<td>0.002</td>
<td>0.22</td>
<td>7040</td>
<td>0.981</td>
</tr>
<tr>
<td>Cx</td>
<td>0.553</td>
<td>0.43</td>
<td>4290</td>
<td>0.960</td>
</tr>
</tbody>
</table>

When discussing the effects of temperature, the parameter of interest is $E_a/R$. $E_a/R$ is a measure of the activation energy for a molecule or segment of a molecule to move from one equilibrium position to another relative to its neighbours [255]. Harper et al. [254] calculated values for $E_a/R$ of 2482 K for cooked cereal dough of 25-30% moisture content using a single screw extruder. Fletcher et al. [246] reported a value of 3969 K for $E_a/R$ with corn grits of moisture contents 15.3-18.7% also with a single screw extruder. The figures reported in Table 6.8 are similar to those starch food materials.

Sample A had the lowest activation energy suggesting that starch molecules move most freely, or require less encouragement to move, in the fundamental thermoplastic matrix.
composed of starch, water and glycerol. This also suggests the least stability at lower temperatures and would help explain the readiness of sample A to experience anti-plasticisation at room conditions. Anti-plasticisation of the starch/water/glycerol system has been studied by Lourdin et al. [314].

The fact that sample B has a higher activation energy is possible evidence of chemical reactions between the starch molecules and the additives of sample B during extrusion. Any cross-linking reactions of TSTMP with starch would inhibit polymer chain movement, as was found with intrinsic viscosity measurements of starch-TSTMP hydrogels at low levels of TSTMP [329]. This would also explain why the shear stresses for sample B in Figures 6.12 - 6.17 are consistently greater than those for sample A. The power law constants in Table 6.8 for sample A and sample B are similar implying that sample B does reflect the basic flow properties of sample A despite the higher stresses in the slit die induced by cross-linking.

Sample C possesses interesting viscous flow properties. Its activation energy is substantially higher than all samples indicating its molecules require the most energy to move. Thus, sample C represents the most thermally stable of the extruded thermoplastic starch samples at low temperatures. Low-temperature viscosity stability has been reported as a property of starch succinates formed by the reaction of starch with succinic anhydride [334]. The bulky ester groups of the starch succinates (shown in Figure 6.5) are likely to contribute to this increased viscosity.

A useful technique for confirming the type of movement of molecules about a polymeric matrix is with the glass transition temperature, T_g. The glass transition is a second order thermodynamic transition in which the sample undergoes a change of state but not a change of phase [344]. DSC thermograms showing the presence of a glass transition are shown in Figure 6.20. (Samples were prepared as described in section 5.3.1).
Figure 6.20: DSC thermograms showing a possible glass transition ($T_g$).

The glass transition is associated with the freezing out of the long range thermal motion of individual molecules and the freezing in of local liquid order [344]. In this case, the exothermic transitions in Figure 6.20 are associated with the melting of the solution of water and glycerol that plasticise the starch molecules within the thermoplastic matrix of the extrudate [345]. Samples A and B have similar $T_g$ peaks at ~6°C, whereas those samples within which starch succinates have been formed, C and Cx, have peak maximums at 2 and -6°C respectively. The exact location is influenced by the rate of cooling during glass formation and the equilibrium value will tend to lie below the measured values [345].

However, the shape of the curves helps determine differences in movement of plasticisers due to changes in the polymeric matrix. Biliaderis [346] noted that the complex morphology of the amorphous regions in the native starch would imply that the thermal properties and plasticisation behaviour of starch by water will vary throughout the amorphous phase. Starch conversion and chemical reactions during extrusion will therefore influence both the position and shape of any exotherm associated with the glass transition. The sample thermograms in Figure 6.20 trace the unfreezing of the amorphous phases.
Samples A, B and C are compounded samples, having been extruded once, whereas sample Cx has been extruded twice. The curves for samples A, B and C reflect what would be expected from a comparison of the values for $E_a/R$ in Table 6.8. Sample A made of starch, water and glycerol has a narrow, sharp peak compared to the other samples, supporting the notion that the plasticising molecules move relatively freely compared to the cross-linked samples B and C. The starch succinates formed in samples C and Cx have an obvious effect on the movement of plasticisers in the material. Although the amorphous phase begins to 'melt' at a lower temperature, the rate of change in the endotherm suggests that the movement is slower when the change occurs. This theory is supported by the higher values of $E_a/R$ for samples C and Cx.

Figures 6.21 – 6.25 compare the predicted viscosity values, $\eta$, (calculated from Eq. 6.8 and the constants in Table 6.4) to the experimental values, $\eta_{ir}$, (calculated from eqn 6.5) against a line of perfect fit. In each case, $R^2 > 0.95$, suggesting satisfactory extrudate viscosity predictions for all samples over the range of experimental conditions chosen.

![Graph showing observed viscosity vs predicted viscosity for Sample A.](image)

Figure 6.21: Observed viscosity vs predicted viscosity for Sample A.
Figure 6.22: Observed viscosity vs predicted viscosity for Sample B.

Figure 6.23: Observed viscosity vs predicted viscosity for Sample Bx.
Figure 6.24: Observed viscosity vs predicted viscosity for Sample C.

Figure 6.25: Observed viscosity vs predicted viscosity for Sample Cx.
Having established a reliable relationship between the empirical models and the data for viscosity, it would have been useful to use the models to predict the flow behaviour during blown film extrusion. But because of the difficulty of obtaining reliable data with respect to the flow properties of the extruded bubble (see section 6.2), no relationship between these models and the behaviour observed during film blowing could be investigated. However, the values of the model parameters were useful in explaining the structural changes of the samples due to mechanical shear, temperature and different additives.

6.5  **Experimental summary**

6.5.1  **Sample extrusion (compounding)**

Untreated wheat starch was combined with plasticisers, water and glycerol, and other additives, TSTMP, methyl(triethoxy)silane and succinic anhydride. Additives were sprayed onto starch granules tumbling in a rotating open pan granulator to produce uniform spherical granules of consistent composition that freely flowed through the extruder hopper. Extrusion speeds and barrel temperature profiles were chosen to produce an extrudate that was not thermally degraded and formed a consistent plastic string that could be pelletised. A foaming extrudate was undesirable because of the inconsistency of extrudate composition and the difficulty in pelletising the foamed string. Approximately 2.5-3.5wt% moisture was lost during compounding.

This method of combining ingredients was successful in providing three basic samples suitable for investigation into blown film extrusion and viscous modelling. Sample A provided the control case and most simple material example, being comprised of untreated wheat starch plasticised with water and glycerol. Sample B included TSTMP and methyl(triethoxy)silane to improve processing properties and moisture resistance. Sample C also included these additives with succinic anhydride added to further improve these same properties. In terms of favourable processability, sample C was better than sample B and both were better than sample A.

All samples readily absorbed moisture as seen in Figure 6.5. TSTMP increased moisture absorption and methyl(triethoxy)silane decreased it to some extent. Succinic anhydride appeared to provide the best resistance to moisture absorption.

Tensile test results (Table 6.4) show tensile properties are very poor. Standard deviations for strain at break and Youngs modulus results indicate essentially no repeatability in all
but two cases where the standard deviation was less than 10% of the sample average. However, these results are the best illustration of the difficulties associated with using a material like untreated wheat starch as a base polymer. Some sort of blending or polymer tailoring, a common process when choosing plastic resins for particular processes or products, would be necessary to obtain material consistency.

6.5.2 Blown film extrusion
There was minimal success with blown film extrusion as Table 6.5 attests. Sample A was unable to be drawn to any extent in the axial or circumferential direction. Samples B and C were able to expand in the circumferential direction up to 2.3 times the annular die diameter, but not so in the axial direction. A minimum film thickness of 0.2 mm was achieved. This is still around 10 times the thickness of a film of HDPE or LDPE used for packaging film purposes. The best results were produced by sample C. The presence of succinic anhydride in sample C appeared to induce a smoother film surface.

The inability of the samples to be drawn in the axial direction can be attributed to the highly branched nature of the untreated wheat starch used. This inability to draw was also supported by the poor tensile test results presented in Table 6.4. More recent work by Thunwall et al. [315] found a similar result with native potato starch. It was far more difficult to process than the hydroxypropylated potato starch used for comparison. However, the urea/formamide used to plasticise high amylose TPS by Zullo and Iannace [318] was able to produce a homogenous film as thin as 50 μm.

6.5.3 Viscosity models
Together with samples A, B and C, re-extruded samples of samples B and C, re-named Bx and Cx were subjected to rheological analysis. A slit-die fitted with pressure transducers was attached to the extruder for gathering rheological data at die temperatures of 120, 140 and 160°C, and screw speeds of 5-50 rpm. A power law fluid model was initially used to establish the effect of shear rate on viscosity. Regression coefficients for these models were typically greater than 0.95 implying acceptable fitting of the data.

Temperature effects were then incorporated by assuming the consistency coefficient of the power law model follows an Arrhenius relationship with temperature. Rheological models predicting viscosity as a function of temperature and shear rate were constructed for all
five samples. Regression coefficients in this case were between 0.957 and 0.981, also suggesting a satisfactory fit of predicted viscosities with the observed viscosities.

Flow behaviours at different temperatures were accounted for by molecular changes, supported by DSC and GPC analyses. Molecular fragmentation induced by mechanical shear was often evident. Comparison of model coefficients, together with DSC and GPC was able to explain the influences of distarch phosphate cross-links formed by starch reacting with TSTMP and starch succinates formed by starch reacting with succinic anhydride.

In terms of processing knowledge, a review by Xie et al. [253] noted that measuring the rheological properties of thermoplastic starch remains difficult due to the volatility of water as a plasticiser and the high processing viscosities compared to the viscosities encountered with petrochemical plastics. This makes in-line extrusion still an attractive method for measuring rheological properties of thermoplastic starches.

### 6.5.4 Conclusions

Despite the low cost of sample production, the starch based plastic materials produced in this study are unsuitable to use as a plastic packaging film. Considering the viscous property changes due to relatively simple alterations to the native starch, water, glycerol matrix, the single biggest improvement would likely come from choosing a more linear polymer structure in the starch, namely a high amylose content starch. The samples’ susceptibility to biodegradation was inferred from knowledge of the sample ingredients, the high rate of moisture absorption in the moisture absorption tests, and the growth of mould that formed during prolonged storage of older samples. Also, according to the standard for biodegradable plastics, AS4736-2006 [33], the samples produced here qualify as biodegradable.

The key knowledge gathered from the experiments though, is that viscous behaviour can be reliably modelled with rheological techniques, and that the flow of the material can be explained by the influence of feedstock composition, processing conditions and the ensuing molecular transformations.
7. A conceptual model of a sustainable system

In terms of performing as a plastic packaging film, the samples produced in the experimental work of chapters 4-6 were left wanting. But they were inexpensive to produce and they were biodegradable. Over the time since the samples were produced almost twenty years ago, products have become available that fulfil the roles of plastic films, many as shopping bags for example, and are marketed also as degradable, biodegradable or compostable materials (see section 3.3.6). These products satisfy requirements of international standards for breaking down after their service life. Those that can be consumed by microbes in the short term, like the samples of the experimental study, essentially fulfil the original objectives of the study, although starch may not necessarily be the polymer of choice for current packaging film products.

Within the same timeframe, technologies that contribute to sustainable industrial practices have succeeded enough to comprise a cleantech sector within stock exchanges (section 1). But, as discussed in section 2.5, there is significant doubt about the effectiveness of any progress in that time. If technological solutions continue to succeed in their aims but progress is still lacking, what other types of solutions can contribute? Moreover though, how quickly does that contribution need to become effective to ensure that progress has indeed been made?

The comparison of ASX cleantech sector data (Table 1.1) and the latest IPCC report data [3] in the introduction provided an ‘at hand’ way of comparing current problems and solutions with respect to SD issues, raising the idea of a ratio between problem proliferation and solution implementation, and how it changes over time. Chapter 2 presented publications on SD that contend with the difficulties of indicators, assessments, decision-making and the general process of creating a more sustainable industrial economy. Chapter 3 provided background information for pursuing an alternative method for describing SD solutions based on concepts of complexity, material flow and a minimum quality of matter being available for life supporting systems to function adequately. This in turn prompted the inquiry into material waste and plastics and the ensuing laboratory work of chapters 4-6 to obtain further knowledge about what influences material flow and transformation on a molecular scale. In this chapter, observations from chapters 3-6 are used to construct a conceptual model of a sustainable system, with a view to addressing some of the challenges summarised in section 2.5, such as system integration, time and complex systems, and the quality of information presented to decision-makers. Features
of the model and considerations for applying the model quantitatively are discussed in section 7.9.

7.1 **Process for constructing the model**

One of the more interesting avenues of research discussed in section 4.1.6 was that of modelling bubble stability during the blown film process, a helpful exercise for optimising the production of a consistent, saleable product. Given the processing conditions and polymeric properties of the material being processed, researchers demonstrate considerable success in predicting the change in shape of the bubble and consequently the film thickness. From a fluid dynamics perspective, the system involved is very complex, yet it is possible to determine that a certain output could be sustained under certain conditions (sections 4.1.5 and 4.1.6).

Remembering the premise from section 3.2 of a system that can sustain life requiring a certain quantity of material of a certain quality, the ability to predict material flow behaviour on the scale of the industrial economy scale is very appealing. The possibility of understanding material flow on a global scale to the degree that material flow is understood in the laboratory would facilitate the development of a system of solutions or the idea of a plan, as described by Ackoff [90], for managing a sustainable system.

The viscosity models of section 6.4 predicted how the rate of flow for a number of starch thermoplastic samples changed with temperature and shear rate, with re-extrusion and with the addition of certain additives. The rheological behaviour could be partly explained by inferring molecular transformations from DSC, GPC and tensile strength analyses. The ability to model and predict material flow behaviour on a global scale would require describing entities on that scale analogous to the polymers and additives within the structure, the geometry of the system and the temperature and pressure profiles. It would be advantageous to determine what influences the viscosity of materials flowing about the industrial economy, and see how disturbances to the flow affect its stability and resilience. It would be possible to assess how sustainable the system is and what develops from it. The conceptual model presented here is an initial attempt to describe a system that can take advantage of rheological concepts and ideally provide tools for assessing and developing sustainable systems. It does this through a series of abstractions of concepts and phenomena relevant to a sustainable industrial economy, such as those of problem solving, complex systems, thermodynamics and material flow and transformation.
discussed in chapters 3-6. A useful description of abstraction for the purpose here is as follows:

'Abstraction is based on a mental process of understanding a phenomenon or system, in terms of constructs that hide or ignore details that are irrelevant for whatever considerations at hand. It also involves a process of identifying or naming objects, properties and interrelationships that hold the essence of what is considered or observed' [112].

To initially account for the complexity of the industrial economic system, the process for constructing the model begins with describing how a total problem/solution system changes over time. It then proceeds to add more detail to the description at each step, aiming to identify fundamental, but practical entities, sets of entities and systems for describing a sustainable system. What defines each step from another is the abstraction of the total system into a form that can support differentiating further information, but is not inconsistent with the steps of abstraction before it.

7.2 Step 1 – Picturing the problem/solution system

Figure 7.1 provides a conceptual generalisation of the iterative process of problem solving. A system of all entities pertaining to a problem, and its solution, S, is represented by a circle. In the case of complex problems, knowledge, Kn, (represented by the white) of the problem and its potential solution, is accumulated through an iterative process over time. At time, t = 0, knowledge, Kn = 0. As time, t, continues, 0 < t < ∞, knowledge of the system, Kn, changes between, 0 < Kn < 1. As knowledge of the system increases (e.g. through research, building tools), system entities become part of that knowledge, and if knowledge of the system decreases (e.g. a skilled employee leaves, or when infrastructure is destroyed in war), those entities are forgotten. At some point, an inherent problem of the system can be resolved.

If the condition can be assumed that if there is no problem then knowledge of the system is sufficient, it is possible to also equate the black and white portions of S to the problem part of the total system, Pbm, and the solution part of the total system, Sln, respectively. This is a useful description in light of interest in determining how the ratio [Pbm]/[Sln] can be used in assessing the sustainability of a system.
In reality, complete knowledge of systems describing complex problems is difficult to achieve if not impossible, as highlighted by the problems associated with sustainable development progress. In theory, maximum knowledge is achieved if all changes of states of material and energy are known \[20\]. Indeed, even what constitutes the size of the system may change with knowledge, as indicated by the varying size of the outer circles in Figure 7.1. But that does not mean that at least some problems can be solved some of the time. Solving a complex problem exists somewhere in the region of time, \(0 < t < \infty\), knowledge, \(0 < Kn < 1\) and \(0 < \frac{Pbm}{Sln} < \infty\). This is simply a formal way of saying that the solver of such problems never knows everything and what is thought to be known could be wrong.

As expressed by Tainter [95] though, it is necessary to know where we stand in the system if we are to ‘face challenges sustainably’. Today’s society in fact, is the first to have the ability to understand where it stands in the process of evolving complexity [4, 95] largely due to the current state of information handling technologies. What version of \([S]\) in Figures 7.1(b)-(e) for example, could represent the current system and how it is changing? The process of developing a biodegradable plastic packaging film might be represented by Figure 7.1(b) in the experimental study of chapters 4-6, but the products available years later as plastic shopping bags may be represented by Figure 7.1(c). There is a need to be aware of how complex systems behave over time and the forms they take. Problems do not stay solved and solutions become obsolete since the system constantly changes [90]. Therefore providing an understanding of time and space relevant to the model is the next step.
7.3 Step 2 – Picturing time and space

In Figure 7.2 a unit of time is defined as the possibility of a system existing in two different states – firstly in one state and then in another.

![Diagram](image)

Figure 7.2: A unit of time, t, is defined as the possibility of a change of state of a system.

To establish what these states could be consider the unit of time as described in Figure 7.3, and assume that state one can change into anything. That is, there are infinite possibilities that state two can assume. At time, t = 0, the system is represented by a point, as in Figure 7.3(a). After a unit of time, t > 0, a process, Tr (transformation), changes the system from state 1 to state 2 (Figure 7.3(b)). The possibilities for Tr are represented by the multiple process trajectories, Tr\(_a\), Tr\(_b\), Tr\(_c\) ... Tr\(_n\) (Figure 7.3(c)). If the trajectory of Tr is represented by the angle of a vector proceeding from the point at time, t = 0, the entire set of possibilities for Tr, for time, t > 0, which are theoretically infinite at time, t = 0, creates a spherical space with a radius that is a function of the time over which the transformative process, Tr, occurs (Figure 7.3(d)).

The concept is similar to that found in Neoplatonic philosophy of ‘the one’ and has been used to describe ‘the start’ in models of natural phenomena (e.g. Kepler [347], the absence of time in interpreting the initiation of the Big Bang [348, 349]). In practice, the concept illustrates the start of decision-making processes to assess and choose future actions. For example, the starch used in the laboratory experiments could have been used for food or fuel.
Figure 7.3: The space ascribed to the possible trajectories a process can proceed along for time, $t > 0$, creates a sphere.

### 7.4 Step 3 – Resources, processes and products

The spherical space of Figure 7.3 may be a representative of the space described by processes over time, but it’s not useful in terms of planning. Good planning requires details such as the initial state, the final state, and how it gets there [90].

#### 7.4.1 Resources

The spherical space of process possibilities defined in Figure 7.3 represents what is available at any instant for a process to occur. The space includes the means of supplying the needs, or the entities that can be drawn upon for a particular process to occur.

At any point in time, including now when time, $t = 0$, there is the theoretical potential for a process or set of processes to proceed in any direction for any length of time, $t$. For the model being constructed here then, a circle will be used to represent a set of resource entities, $Rs$, as shown in Figure 7.4.

Figure 7.4: A circle is used to represent the set of resource entities, $Rs$. 
By definition, Rs, is the set of resource entities necessary at a point in time and space for a process, or set of processes, Tr, to occur in the future.

### 7.4.2 Processes

Resources cannot instantaneously become products, but require processes over time to occur between the two. In Figure 7.5, an equilateral triangle with a side length equal to the diameter of the circle representing the set of resources is used to represent the set of processes particular to transforming that set of resources to the corresponding set of products.

![Figure 7.5: A triangle is used to represent the set of processes, Tr, occurring over a period of time, t.](image)

Symbolically, the point of the triangle bisected by the perpendicular to the centre of the opposing base line represents the point at which the surfaces of two theoretical spheres, like that depicted in Figure 7.3, generated by two different points at time, \( t = 0 \), intersect with each other and superimpose to collapse to the process that does, in fact, occur. That is, all other possibilities disappear once multiple spheres generated by multiple points at time, \( t = 0 \), meet at a single point which, when continuing, constitutes the timeline. It can possibly be visualised as a foaming of spheres that interact and combine over time into a single identifiable system.

Tr is the set of dynamic entities, or actions, that transform a set of resources, Rs, into a set of products, Pr, over a period of time, t.

### 7.4.3 Products

A set of resources, Rs, acted upon by a set of processes, Tr, results in the production of a set of products, Pr. For the purposes of the model representation, a square with a side length equal to the diameter of the circle associated with the set of resources, and the side
of the triangle associated with the set of processes, is used to represent the set of products, as shown in Figure 7.6.

![Figure 7.6](image)

Figure 7.6: A square is used to represent the set of products, Pr.

Symbolically, the product set square can be thought of an area on the surface of the spherical space of process possibilities at time, \( t > 0 \), in Figure 7.3. The square represents that tangential point on the outer surface of the spherical space, at the tip of the triangle in Figure 7.5, where spherical spaces generated by multiple points at time, \( t = 0 \), meet at time, \( t > 0 \). That is, it represents physical reality.

Pr is the set of entities resulting from the actions of a set of past processes, Tr, which have acted upon a set of resources, Rs.

### 7.4.4 The fundamental unit of a process system

The set definitions of Rs, Pr, and Tr constitute the unit of time described in section 7.3. Referring to Figure 7.2, the ‘system in state 1’ is equivalent to Rs, and the ‘system in state 2’ is equivalent to Pr. The process between state 1 and state 2 in the unit of time of Figure 7.2 is equivalent to Tr of Figure 7.5. Combining these together, the fundamental unit, or monad, of a process system can be represented as shown in Figure 7.7.

![Figure 7.7](image)

Figure 7.7: The fundamental unit, or monad, used to describe a process system.

The monad is representative of a unit or period of time. It may be considered analogous to a monomer unit of a polymer. By using it below as the building block to describe a
sustainable system, awareness of time and the implications of that are embedded within any system description. The outer line of Figure 7.7 is equivalent to the outer surface of the space of process possibilities described in Figure 7.3. It is the set of resources, Rs, described in Figure 7.4 that both envelops and is transformed by Tr to produce Pr, over a period of time, t. The thicker outer line of monad representation and that of Rs aims to convey their equivalence.

The monad expresses that resources, processes and products cannot exist without reference to each other in the terms of this model. One cannot exist without the existence of the other two. That is, entities do not exist in isolation. What exists now is because of what has come before, and what is to come is because of what exists now. From this perspective, Figure 7.7 describes the fundamental unit of a process system imbued with a premise of time and flow. It is a representation that ensures that when describing a system, consideration of both where entities have come from and where they are going to is incorporated into the description of the current process. It will be referred to as the RTP system from this point on.

7.4.5 Defining the RTP system

Figure 7.7 represents the adoption of a process perspective, where a process is defined as the central subject together with the ‘different types of events that the central subject endures or makes happen’ [350]. Any entity of any of the resource, process or product sets can be used as a starting point to define the system. Often though, the most practical starting point for describing a system will be within the set of products. The experimental work was instigated by the effect of waste products, for example. Therefore, the research plan began by focusing upon the product of plastic packaging film (section 4.1.1 - 4.1.3). From there, the process of blown film extrusion (section 4.1.4 - 4.1.6) and the starch feedstock to address the waste problem (section 4.2.1 - 4.2.2) were considered.

The second thing to consider is where to draw the boundary of the system. In Figure 3.4(c), the processes of granulation, reactive extrusion and blown film extrusion can each be described individually with the monadic RTP system. That may provide some value if comparing different options for performing those individual processes, but may be of less value in describing how they contribute to a sustainable system overall. The problem of plastic waste (Figure 3.4(a) & (b)) requires a boundary encompassing the source of feedstock (i.e. wheat or oil and gas reserves) and the environment to which the waste
products go. Ultimately, the system boundary is a subjective choice dependent on the motivation for studying the system in the first place. A fuller explanation of using the RTP system by way of describing the experimental work is included in chapter 8.

What uniquely identifies the system, however, irrespective of the boundary is the set of processes within the process system. As explained above in section 7.4.4, resources are products of past process systems, and products are the resources of future process systems. That means that the set of processes, Tr, within the process system is the unique identifier of the system.

7.5 Step 4 - A system without material waste

Plastic packaging waste in the environment was the motivation for the experimental study, and therefore it is necessary to extend the experimental study system boundary beyond that of the manufacturing process and consider its context further.

One trait of a dynamic system of finite matter is there can be no accumulation of material waste within it if it is to be sustainable. Waste can be defined as something that is unusable by, unwanted by, or worthless to a particular system. In practice then, at the very least two process systems need to be defined for the possibility of zero waste accumulation – the one that produces the waste, and another that regards that first system’s waste as usable, wanted or of worth.

As stated in section 7.4.4, entities and the systems they are part of, do not exist in isolation. Figure 7.8 illustrates this fact showing there is always an environment existing external to it from which, and to which, there is a flow of entities over time.

Figure 7.8: A system and its environment from which and to which entities flow.
In Figure 7.9 a sequence of three RTP systems are joined together as a representation of how the flows of Figure 7.7 can be re-interpreted. The system of original focus, \( S^0 \), is preceded by the system, \( S^{-1} \), in the environment from which entities flow to \( S^0 \), and followed by the system \( S^1 \), to which entities flow from \( S^0 \).

![Diagram of three RTP systems](image)

**Figure 7.9:** Figure 7.8 re-interpreted using the RTP system of Figure 7.7.

It is necessary to point out an important rule associated with the RTP system depiction of Figure 7.7 as it is used in Figure 7.9. That is, there is no *physical* transformative process involved between the product of one system and the resource of the next in the depiction of Figure 7.9. The line linking the product end of one system to the resource end of another represents the fact that the product of one system has value, or has utility as a resource to the future process of another system. The link represents a *transformation of perception* from the perspective of the process systems. That is, the only rule to follow for depicting any sequence of processes using the RTP system unit is that products of one system are the resources of a future system, and the resources of one system are the products of a past system. This is a result of adopting a process oriented view for analysis [350].

For example in Figure 7.9, system, \( S^0 \), could represent the extrusion process system used in the laboratory, system, \( S^{-1} \), could be the granulator, and system, the film blowing apparatus. Or the more encompassing scenario associated with the material waste problem could be defined where systems, \( S^0 \), \( S^{-1} \), and \( S^1 \), are defined as processes of the industrial economy, resource processes of supplying petrochemicals or starch, and the processes of the waste stream respectively.

Ecosystems sustain themselves through a continual flow of matter and energy from one part of the system to another. What may be considered waste by one part of the system is accepted as a resource by another part of the system. There is no accumulation of material waste in a healthy functioning ecosystem [85]. In Figure 7.10, Figure 7.9 has
been expanded to portray both the increase in time and the number of processes involved in creating and maintaining an ecosystem.

Figure 7.10: Extending Figure 7.9 to illustrate the continual flow of materials in an ecosystem from one process to another over time.

Over time, there is complete and constant cycling of all materials in an isolated system, in accordance to the first law of thermodynamics, and so the entire sum of process systems in that time can be represented as shown in Figure 7.11.

Figure 7.11: An isolated system showing continual material flow cycling via coupled RTP systems of concentrative and dispersive processes.

In Figure 7.11, one RTP system may represent all processes in the Earth system that concentrate species of matter within a system, as in the case of the growth of living organisms or crystalline structures, and the other RTP system may represent the dispersive processes, such as dissolution and decay. This is similar to the type of process definition used to support the first three principles of The Natural Step [17].

Figure 7.11 can be incorporated into Figure 3.2 to represent the continual flow of matter in the Earth system being driven by the supply of high quality, low entropy energy provided by the sun as discussed in Section 3.2, to produce a representation of a sustainable system in Figure 7.12.
Up until now, the concepts described have accounted for time in a system and the space created by systems through processes. In Figures 7.11 and 7.12, the third fundamental feature of complex systems of feedback relationships between systems is identified by the links between the two coupled systems (section 3.1.1).

![Diagram](image)

Figure 7.12: Incorporating Figure 7.11 into Figure 3.2 produces a model of a sustainable system.

### 7.6 Step 5 – Natural, human and economic entities

Figure 7.12 may model the concepts of a sustainable system, but the truth is it is representative of any material body within a ray of a solar energy source. The laws of thermodynamics still apply beyond the Earth system. What sets the Earth system apart is that the processes that have evolved through millennia according to the laws of nature have established a myriad of transformational opportunities allowing a general flourishing of diverse life. In sum, there currently is within the Earth system a flow and transformation of matter that moderates entropic losses in a way that develops and sustains life, rather than suppresses it. The dynamics of this particular complex system result in the self-organising processes of life (section 3.1.1). It is this system of life-sustaining material flow and transformation and the role of human activity in it that is of prime interest in the discussion of sustainable systems and sustainable development. It is first necessary to differentiate the types of resources, processes and products in this system to a degree that will assist in its analysis.
Continuing with the spherical space of Figure 7.3, if the radius of the sphere represents the length of time associated with its processes, new biological processes appear over time with evolution. The new system of processes is always going to be represented by a sphere smaller than the original, since it has existed for less time, as shown in Figure 7.13, where $T_{r1} > T_{r2} > T_{r3} \ldots > T_{rn}$. If one system of processes disappears due to extinction, all smaller ones that evolved from that set and along that line disappear as well.

![Diagram](image)

Figure 7.13: Through time, $t$, the space of possible natural processes, $S_1$, yields a space of possible processes, $S_2$, which in turn yields a space of possible processes, $S_3$, and so on to $S_n$.

In Figure 7.14, the spheres of Figure 7.13 have been superimposed. Technically, the spheres, or systems, would not share the same centre since they emerge at different points along the initial process trajectory over evolutionary time, but they would share a common point on their circumferences representative of them all existing concurrently, as shown in Figure 7.14(a). However, for practical purposes, this has been normalised to give the concentric arrangement of Figure 7.14(b) that will be used for the remainder of the model description.

In reality these systems could represent the processes associated with the development or evolution of any species. However, it is the processes of humanity that are of interest in this discussion. If humanity is considered in this description of process evolution, Figure 7.13 is representative of the fact that the system of possible natural processes is greater than that of the system of human processes, $S_1 > S_2$ for example. The system of human processes is in turn greater than that of the processes that humanity develops, $S_2 > S_3$ for example.
Generally speaking, the processes that humans have developed are those of the industrial economy. Economic processes have been developed to manipulate attributes of the human environment towards a desired state. In short, natural processes give rise to human processes which give rise to economic processes of industry. This progression is illustrated in Figure 7.15. Technically, any system of processes developed by humans, agriculture, mineral extraction, information technology, could comprise a further system of possible processes, being a subset of the definition of modern industrial economic processes.

Transposed onto a single area similarly to Figure 7.14 above, the comparable spaces would appear like that shown in Figure 7.16, where $S_N$ is the natural process system, $S_H$ is...
the human process system, and \( S_E \) is the economic process system. The key point in this representation is that the natural system encompasses the human system, which encompasses the economic system.

![Diagram](a)

Figure 7.16: The comparable sets of resource entities for the natural, \( S_N \), human, \( S_H \), and economic, \( S_E \), systems in technically correct, (a), and normalised (b) forms.

The RTP system, by definition of a monad and as described in section 7.4, is central to and part of all natural, human and economic process systems, as shown in Figure 7.17.

![Diagram](b)

Figure 7.17: The set of economic entities, \( S_E \), is a subset of human entities, \( S_H \) which in turn is a set of natural entities, \( S_N \), to each of which the monadic RTP system is part of and central.

This portrayal is similar to the three pillars or TBL framework definitions that are often seen in sustainability discourse (see section 2.1.3), though the methods of describing it may vary. For example, Boyden and Dovers [351] use these words: ‘Despite the spectacular
advances in technology, humans and their cultures are still and forever will be, embedded in and entirely dependent on the underlying processes of nature for their very existence.’

It is only ‘similar’ though, because there is a key fundamental difference between Figure 7.17 and the conventional means of segregating the system entities of sustainability discussions. That is, Figure 7.17 doesn’t distinguish a ‘social’ or ‘cultural’ realm unto itself. The distinction between $S_N$, $S_H$, and $S_E$ is made purely on the types of processes each encompasses.

### 7.6.1 Distinguishing natural, human and economic entities

Consider Figure 7.15 from the perspective of the RTP description in section 7.4.4 and Figure 7.7. Nature and the set of natural processes are the ultimate set of resource entities, $R_s$, that have been transformed by the set of human process entities, $T_r$, to produce the set of economic product entities, $P_r$. What this interpretation yields is a RTP system on the time scale of millennia associated with the Earth system, as shown in Figure 7.18.

![Diagram of the economy as a product of human processes acting upon the resources of nature over the time scale of millennia.](image)

Figure 7.18: The economy is a product of human processes acting upon the resources of nature over the time scale of millennia.

The set of resource entities of that system is nature, which includes matter, energy and the processes that transform them. The set of human entities is within that set of natural resources, as per Figure 7.17. But what distinguishes human entities apart from other
forms and processes of matter and energy is the extent of cognitive comprehension they possess of the natural system from which those same human entities arose. In fact, that comprehension exists to the degree that allows them to be the process system. It is the ability of humans to collate data, assemble information and develop knowledge of the natural system that makes them the most effectual entities at transforming their environment above all other biological entities in the biosphere [352].

So then, if the currency of the natural system can be considered as the flow of energy and matter, it is the flow of data, information and knowledge that make up the currency of the human system [11]. It is a currency that defines it as the set of transformative processes in Figure 7.18.

The existing forms of energy, matter, data, information, knowledge that humans choose to manipulate is driven by the value humans ascribe to the future material forms of those entities, whether they be for basic sustenance or for gratifying the imagination, as discussed in section 3.2. Therefore, although products of the industrial economic system may be composed of matter and energy of the natural system, or of information of the human system, an entity of the economic system is discerned from the natural and human systems by having a future value attributed to it by the human system. (As an explanatory aside, it would be possible to replace ‘human system’ with any other living system that acts to secure its future, such as a bird building its nest, and then talk of the economic system produced by the bird.)

The currency of the economic system is derived from the relative values of its entities and this is what has evolved into the various monetary devices used today and historically. (For the inspiration for distinguishing natural, human and economic entities in this manner, refer to Binswanger’s depiction of the realms of science, art and economics as humanity’s attempt to overcome transitoriness by immersing itself in the past, present and future respectively [121].)

It is now possible to quantify some entities of each of these systems with their own particular units. For example, energy and matter can be measured in kilojoules (kJ) and kilograms (kg), data and information in bytes or kilobytes (KB) and an example of a monetary device is dollars ($). Rather than the lateral flow of material transformation shown in Figure 7.18, it may help to picture the different currency flows between the three
systems in a vertical manner, as shown in Figure 7.19, together with example units of currency flow measurements.

In practice, describing entities will involve a combination of objective quantities and subjective qualities \([11, 47, 94]\). But, the main point is that in any material process of the industrial economy, there exist three parallel flows of defined currencies that facilitate the transformation:

- Energy/matter of the natural system;
- Information/knowledge of the human system; and,
- Value/money of the economic system.

![Figure 7.19: The sets of natural, human and economic entities alongside example units of currency measurement.](image)

The coupling in each case of energy/matter, information/knowledge and value/money is used to convey the fact that there is a combination and variety of continuous and discrete entities that make up each of the currencies. For example matter is a discrete form of energy; money is a discrete form of value; and the continuity of entities within the currency of the human system changes between data, information, and knowledge through to its judicious application in wisdom \([11]\).

In terms of describing an entity that would normally be associated with society or culture in conventional interpretations, the entity is shared amongst the natural, human and
economic process systems. For example, satisfactory labour conditions in a factory would constitute a combination of the matter and energy of the humans, the information and knowledge distributed between and held by employer and employee, the monetary arrangement between the two, as well as the type of value ascribed by the employee to the work, as well as the value ascribed by the employer to the employee. This manner of distribution of human factors according to the three separate currencies is explained further in chapter 8. The method does, however, open the possibility of an alternative way of describing social or cultural indicators that can be difficult to handle [11, 42, 47].

7.7 Step 6 - Organising system information

At this point, the various types of entities within a complex system that is being assessed for sustainability can be described as belonging to the natural, $S_N$, human, $S_H$, or economic, $S_E$, systems, or a combination of any of the three (sections 7.4 and 7.5). They can also be described as belonging to $R_s$, $T_r$, or $P_r$ sets of a process system, but only to one of these, depending on the definition of the process system (section 7.4.5). To describe a process system completely for analysis then, the three concurrent flows of the natural, $S_N$, human, $S_H$, and economic, $S_E$, systems need to be considered as they combine in the unfolding of a process, $T_r$, from resources, $R_s$, to products, $P_r$. To do this, Figures 7.17 and Figure 7.19 are combined as shown below in Figure 7.20, to give the final representation in Figure 7.21.

![Figure 7.20: Combining Figure 7.17 with 7.19.](image-url)

Figure 7.21(b) replaces the ellipses of $S_H$ and $S_E$ in Figure 7.21(a) with shapes closer to that of the original process triangle and product square descriptions of section 7.4 to...
emphasise they are distinctly separate flows that occur due to different types of processes, but still derived from the RTP system definition. $S_N$ is subject to natural processes (the triangle in the circle), $S_H$ is subject to human processes (triangle in the triangle) and $S_E$ is subject to economic processes (triangle in the square). ‘S’ represents the total system, $S_{O}^{0}$, is assigned to the process system of focus or of observation. The subscripts represent the natural, N, human, H, economic, E and observation, O, systems. The superscripts represent either the system before, ‘-1’, or after, ‘1’, the system of observation, $S_{O}^{0}$, whose superscript is ‘0’.

Figure 7.21: (a) The representation of all entities, sets and systems of the total system, $S$; (b) With alternative shapes to discern between $S_N$, $S_H$ and $S_E$ types of processes.
7.7.1 Information matrix format

At this point, there are enough entities, sets, systems and interrelationships between them described in Figure 7.21 to provide a practical tool for organising information associated with a process system and for assessing and developing its sustainability.

Table 7.1 lays out a matrix in a format for holding the types of information pertaining to each of the elements of Figure 7.21 with examples of the type of elements. In practice, the entities will depend on the choice of system boundaries in the analysis as stated above. The ‘Change in resource utility (ΔRU)’ in the bottom row is in lieu of a definitive way to quantify the quality of a resource, as discussed in section 3.2.2. How this change is expressed in practice will depend on the prerogative of the analyst and therefore its units are depicted by a question mark in brackets, (?).

The shading of the cells in Table 7.1 correlates the relationships of the systems in Figure 7.21 with their informational relationships. For example, the transformative processes, Tr, of each of the RTP systems have a characteristic time, t, and change in resource utility, ΔRU. The products, Pr, of S⁻¹ systems are the resources, Rs, of the S₀ system. The resources, Rs, of the S¹ systems are the products, Pr, of the S₀ system. The thicker border around the cell depicting the processes, Tr, of the system being observed, S₀, highlights it as that of the present moment and centre of the total system, S.

The notation of S, S₀ and S₀ all refer to the system of observation, but what is used depends upon the form of the model being applied. The simplest form, S, is used for a monadic RTP system description. In that case, there is only one set of resources, Rs, one set of processes, Tr, and one set of products, Pr, required to complete the description. S₀ is used when the analysis extends to including systems external to the observed system, such as the system before, S⁻¹ and system after, S¹ and the corresponding sets within are written as [S¹]-R for the resources of the system after, for example.

S₀ is used for the more complex case where entities of sets are divided into the natural, Sₙ, human, Sₕ, and economic, Sₑ systems and external systems are also included. For example, Sₙ is the system of matter and energy previous to the system being observed. This is the notation assigned to the configuration displayed in Figure 7.21.

The combination of the model diagram in Figure 7.21 together with the layout of Table 7.1 proposes to provide a tool suitable for assessing and developing systems for their
sustainability. Information pertaining to Rs, Tr, or Pr sets of each of the individual RTP systems, as well as the time, t, and the change in resource utility, \(\Delta RU\), associated with each can be recorded in a simple, logical manner.

Table 7.1: Matrix for recording information associated with the total system, S, illustrated in Figure 7.21 with suggested nomenclature in bold type.

<table>
<thead>
<tr>
<th>System notation (example units)</th>
<th>(S_{\text{W}^1}) (kJ, kg)</th>
<th>(S_{\text{H}^1}) (KB)</th>
<th>(S_{\text{E}^1}) ($)</th>
<th>(S_{\text{O}^0}) (kJ, kg, KB, $)</th>
<th>(S_{\text{H}^1}) (kJ, kg)</th>
<th>(S_{\text{E}^1}) ($)</th>
<th>(S_{\text{H}^1}) (kJ, kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rs</td>
<td>Energy/matter resources of system (S_{\text{W}^1}), ([S_{\text{W}^1}])-Rs</td>
<td>e.g. any form of energy/matter</td>
<td>Information/ knowledge resources of system (S_{\text{H}^1}), ([S_{\text{H}^1}])-Rs</td>
<td>Value/ monetary resources of system (S_{\text{E}^1}), ([S_{\text{E}^1}])-Rs</td>
<td>Total resources required for system (S_{\text{O}^0}), ([S_{\text{O}^0}])-Rs</td>
<td>Energy/matter products of system (S_{\text{H}^1}), ([S_{\text{H}^1}])-Rs</td>
<td>Information/ knowledge products of system (S_{\text{E}^1}), ([S_{\text{E}^1}])-Rs</td>
</tr>
<tr>
<td>Tr</td>
<td>Process of system (S_{\text{W}^1}), ([S_{\text{W}^1}])-Tr</td>
<td>e.g. all natural processes, industrial processes of energy/matter transformation</td>
<td>Process of system (S_{\text{H}^1}), ([S_{\text{H}^1}])-Tr</td>
<td>e.g. reading, observing, perception, invention, innovation</td>
<td>Process of system (S_{\text{E}^1}), ([S_{\text{E}^1}])-Tr</td>
<td>Process under observation. Process of focus. Process of system (S_{\text{O}^0}), ([S_{\text{O}^0}])-Tr</td>
<td>Process of system (S_{\text{H}^1}), ([S_{\text{H}^1}])-Tr</td>
</tr>
<tr>
<td>Pr</td>
<td>Energy/matter resources of system (S_{\text{O}^0}), ([S_{\text{O}^0}])-Pr</td>
<td>e.g. electricity, labour/ equipment, feedstocks</td>
<td>Information/ knowledge resources of system (S_{\text{H}^1}), ([S_{\text{H}^1}])-Pr</td>
<td>e.g. operating procedures/ scientific knowledge</td>
<td>Value/ monetary resources of system (S_{\text{E}^1}), ([S_{\text{E}^1}])-Pr</td>
<td>Total products of system (S_{\text{O}^0}), ([S_{\text{O}^0}])-Pr</td>
<td>Energy/matter products of system (S_{\text{H}^1}), ([S_{\text{H}^1}])-Pr</td>
</tr>
<tr>
<td>Time, t</td>
<td>Time required for process of system (S_{\text{W}^1}) to occur, (S_{\text{W}^1}(t))</td>
<td>Time required for process of system (S_{\text{H}^1}) to occur, (S_{\text{H}^1}(t))</td>
<td>Time required for process of system (S_{\text{E}^1}) to occur, (S_{\text{E}^1}(t))</td>
<td>Time required for process of system (S_{\text{O}^0}) to occur, (S_{\text{O}^0}(t))</td>
<td>Time required for process of system (S_{\text{H}^1}) to occur, (S_{\text{H}^1}(t))</td>
<td>Time required for process of system (S_{\text{E}^1}) to occur, (S_{\text{E}^1}(t))</td>
<td>Time required for process of system (S_{\text{H}^1}) to occur, (S_{\text{H}^1}(t))</td>
</tr>
</tbody>
</table>

\(\Delta RU\) (kJ, kg, KB, $)
7.7.2 Determining the sustainability of the observed system, $S_0^0$

Figure 7.21 and Table 7.1 together provide a tool for organising data information. Data and information from whatever sources, such as that determined through the metrics, indicators and assessment methods discussed in section 2.2 can be laid out for analysis and assessment of the system being observed, $S_0^0$.

By including time, $t$, for the systems, the rate of changes in the ‘stocks’ [11] (or ‘capitals’ [27]) of resources, $R_s$, and products, $P_r$, and the flows of transport and transformation of the processes, $T_r$, within each of the $S^{-1}$, $S^1$, as well as the observed system, $S_0^0$, together with the continuity with which entities are perceived to be resources, $R_s$, or products, $P_r$, from the perspective of a process, $T_r$, can be scrutinised. Changes in the resource utility, $\Delta RU$, across process systems can be considered amongst the influences upon flows and transformations of not only matter and energy, but of value and money and information and knowledge within the total system, $S$. They can be isolated to within or between one and more of the seven RTP systems. Something analogous to the rheological properties of a material responding to the influences of temperature, pressure and shear can be ascertained with respect to the system, $S$, as a whole.

As analysis of system, $S_0^0$, proceeds, turnover time and coverage time of stocks, and the harvest or regeneration, emission or absorption [11] of flows of materials can be added. Cyclic flows where a product, $P_r$, from a system, $S^1$, appears as a resource in a system, $S^{-1}$, or the lack of them can be recognised. The options available for a resource, $R_s$, product, $P_r$ or process, $T_r$, contributing to the diversity, flexibility of the overall resilience of the system, $S_0^0$, can be identified and the sustainability of the system can be assessed and developed.

In practice, all relevant information is unlikely to be initially at hand. But, as stated in section 7.1 and illustrated in Figure 7.1, solving the problems of a complex system is an iterative process, and where possible information can be attained over time and added to the knowledge of the total problem/solution system (Figure 7.1).

7.8 Step 7 – Extending Figure 7.21

Organising the information according to Figure 7.21 and Table 7.1 serves a practical purpose as they stand, which will be demonstrated with the examples in chapters 8 and 9. However, to return to the idea of determining the rate of problem proliferation to the rate of
solution implementation, it is necessary to combine, or integrate, a great many $S_0$ systems. Figure 7.22 illustrates how this is possible with the current method of organising information.

In it is shown how the observed system, $S_0$, is related to its associated resource systems, $S_{N^{-1}}$, $S_{H^{-1}}$, $S_{E^{-1}}$ and product systems, $S_{N^1}$, $S_{H^1}$, $S_{E^1}$. For example, the circle in the shaded ellipse of system, $S_{N^{-1}}$, represents an entity of the set of products in $S_{N^{-1}}$ that is a resource, $R_s$, for $S_0$. Secondly, the dashed replica system near system, $S_{H^{-1}}$, is a reminder that each of the six systems before and after, systems $S^{-1}$ and $S^1$, are, in fact, *sets of systems*. For example, the data, information, and knowledge resource entities that contribute to the set of resources, $R_s$, in the observed system, $S_0$, are product entities from a *number of systems* that together comprise system, $S_{H^{-1}}$.

Figure 7.22: Extending Figure 7.21 to illustrate the relationship of the observed system, $S_0$, to its externally connected systems.

The original analysis is from the perspective of system, $S_0$. But by following the relationships in Figure 7.22, the focus can be shifted and the original system of observation can become one of the connected systems to the next system of observation. An identical analysis to that described above in section 7.7 can be carried out for the new system of observation and then the analysis can shift to another connected system, and so on. If many systems are defined and analysed as system, $S_0$, with the connective properties of the links between them preserved, it will be possible to see how entities are
shared amongst a network of systems. As the scope of the total system expands, it will be seen that entities appear in multiple systems and in before, $S^{-1}$, and after, $S^1$, systems with respect to any particular system of observation, $S_0^0$. In turn, feedback processes and non-linear behaviour typical of complex systems will appear [100, 101].

Ultimately, it is theoretically conceivable that many, many systems can be intermeshed, not unlike the molecules of a polymer matrix, to form a multi-dimensional fabric of which the flow and transformation of entities can be ascertained. In total, this integrated system can be similarly depicted as the total system, $S$, in Figure 7.1 containing the problem, [Pbm], and solution, [Sln], parts changing over time. Theoretically, regions where the fabric flow is stable could be determined for certain network parameters. The sustainability of the fabric could be related to the continuity of its flows and the development of its transformations could be related to its shapes and contours. In turn, the ratio between the rate of problem proliferation and solution implementation, [Pbm]/[Sln], could be provided by the dynamics of the fabric and determining its criteria for resilience to both endogenous and exogenous disturbances.

### 7.9 Discussion of the model

#### 7.9.1 Features

In Figure 7.1, the [Pbm]/[Sln] is dependent upon the change in knowledge of the system, $Kn$. It is possible for this process to be expressed mathematically by applying the concept of Shannon entropy where the information in a message is defined as the difference between two entropies, or uncertainties - the first associated with knowledge, $Kn$, before a message and the other associated with knowledge, $Kn'$, after a message [114, 117]. It can be interpreted as the dynamics of resolving a mess, denoted by the total system, $[S] = [Pbm] + [Sln]$, by extending knowledge, $Kn$, to devise a system of solutions, [Sln], or a plan [90] as more information comes to hand with time. It would also be possible to interpret the fluctuations of the size of the mess and what is known about it at a certain point in time as the dynamics of a wicked problem [97] where there is no optimal solution, but a continual to and fro of difficulty and resolution. The system is sustainable as long as [Pbm]/[Sln] does not continue towards infinity, which requires the maintenance and growth of knowledge, $Kn$.

The description of time, $t$, in section 7.3 at the very beginning of describing the mechanics of the model, immediately introduces a dynamic premise to the model. By further defining
resources, Rs, processes, Tr, and products, Pr, as sets of a monadic RTP system, and using that system as a building block, time and dynamic flow is the foundation for constructing the model. This addresses the pertinent issue often remarked upon in the literature: that of time and dynamics being included in the development of sustainability assessment tools [10, 11, 17, 73, 92].

Secondly, all possible future states are borne from what the set of resources, Rs, deems possible. This facilitates a true integration of systems and concepts during an assessment through a growth of systems and entities from a single beginning, rather than simply being accumulative, as is almost always the case in sustainability assessments to date [42, 65, 66]. Structurally the monadic RTP unit is a divisible whole where Rs, Tr, and Pr need to be identified as distinct entities for analysis. But functionally it cannot be divided, since the existence of one relies on the existence of the other two [90]. All three are integral to one another. The ability to integrate disparate parts of system into a common understanding is a key requirement for performing assessments that suitably inform the decision making process [63, 66, 74, 77, 80, 353].

Thirdly, by building the model from the RTP system, the construction is very adaptable by virtue of how Rs, Tr and Pr can be defined from the perspective of the analyst and for any transformative process where the entities involved are matter and energy, information and knowledge or value and money. System boundaries can be defined from the perspective of the assessor and the model is open to diverse definitions and principles of sustainability [12] as well as the measurements and assessments employed [11]. Resources are products from an earlier system and products are resources for a future system, so it is the process within a RTP system that is unique and therefore provides the locus for system boundary definition [350, 354, 355].

When several RTP systems are linked together, as illustrated in Figure 7.10, the similarity to LCA appears [42, 48-50]. In fact, if the process systems are defined for matter and energy transformations, the model is quite identical to a system definition that is suitable for applying the Eco-indicator 95 [51] and Eco-indicator 99 [53] LCA tools and deriving the various impacts for effects such as greenhouse effect or acidification. Calculating exergy changes across individual and aggregated process systems as part of LCA will reveal the changes in resource utility that reflect overall efficiencies [128, 129].
Expanding the RTP system from matter and energy flows in section 7.6 to flows of information/knowledge and value/money is reminiscent of the TBL framework [21, 22, 63]. However, there is a fundamental difference. The natural, human and economic systems are defined by types of processes. Humans, $S_H$, are ascribed the role of processes, $Tr$, in an RTP system defined with a timescale of millenia, between the resource processes of the natural system, $S_N$, and the product processes of the economic system, $S_E$. In this description, there is no distinct 'social' realm to speak of. It is split between $S_N$, $S_H$, $S_E$.

For example, the social issue of working conditions would be a combination of satisfactory equipment and work space of material and energy flows in $S_N$, the communication and intellectual requirements of knowledge and information flows of $S_H$, and value and monetary flows of $S_E$. The interrelation of these flows would determine social indicators.

Figure 7.21 and Table 7.1 present the practical starting point for an assessment in the terms of the model presented here rather than one that resembles LCA. Information and knowledge pertaining to a system is organised into the 21 cells of Table 7.1 and the flows of material/energy, information/knowledge and value/money that exist and those that can be developed are presented in a readily accessible format. As such, the requirements [119, 120] for uncovering the system of problems and designing a plan to deal with them can be formulated through an iterative application of Table 7.1.

Figure 7.22 shows how the system of focus for the original analysis, $S^O_0$, is connected to systems that become before and after it. It is knowledge, $K_n$, of this expanded representation that allows the ratio $[Pbm]/[Sl_n]$ and hence the sustainability of the system to be determined. Although a method to perform this is not included here, a method similar to that of Ulanowicz et al. [111] for quantifying the resilience of a system may very well be suitable for this purpose. The growth or recession of knowledge, $K_n$, of a system can be implicated by the known presence and absence of links between systems of the extended network in Figure 7.22 and its resilience determined in the fashion of Ulanowicz et al. [111]. It is also possible that by focusing on the existence of links between individual systems, that is, the flows of matter/energy, information/knowledge and value/money between them, rather than the details of resources, processes and products within the RTP systems, the problem of access to quality data can be mitigated. In determining the network structure to be analysed, Figure 7.22 can also be compared to the tree structures developed for a product in EEIO analysis where the associations (the links) to upstream and downstream entities are evaluated [70].
Alternatively, if the backcasting method [33] of defining a sustainable system is applied, a particular network of systems describing a future desirable state be formulated and the comparison between the links that exist now and those that exist in the future desired state could provide a blueprint for what needs to be done for create a sustainable system.

The ideal method of quantification for the sustainability of the networked system would be to strengthen the analogy of its structure to that of a polymeric fluid. If an RTP system is a monomeric unit and a network of them is a polymer fluid, the viscous properties and flow stability and resilience to disturbances would allow very interesting models of dynamic behaviour to be developed in a similar manner to the models of film blowing that contribute to optimum control of the process (see section 4.1.5).

7.9.2 The model and complex systems

It is useful to note the model’s suitability for representing complex systems by comparing a its properties to the suggested characteristics of a complex system listed by Bishop [100]. If the model can represent essential features of the structure and behaviour of complex systems, methods of quantification, discussed in the following section 7.9.3, will develop more lucidly. Table 7.2 lists how features of the model described in this chapter compare with the list provided by Bishop [100].
Table 7.2: Comparison of model properties to complex system features.

<table>
<thead>
<tr>
<th>Complex system properties [100]</th>
<th>Model features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Many-body systems— the number of bodies that yield system complexity depends on the behaviour of individual bodies and their influence upon each other.</td>
<td>The analyst can re-interpret a real-world system according to the model by introducing as many RTP system units as is practical.</td>
</tr>
<tr>
<td>Hierarchy— levels or nested structures (e.g. large scale flow of starch as plastic packaging in economy vs. small-scale flow of starch molecules in plastics extruder).</td>
<td>The system boundaries in the model are defined by the analyst. There is no prerequisite of size of scale. Therefore hierarchies and nested structures can be described.</td>
</tr>
<tr>
<td>Irreversibility – distinguishable hierarchies usually result from irreversible processes.</td>
<td>Defining the RTP system as a unit of time and considering the change in resource utility or exergy across it accounts for irreversibility of real processes.</td>
</tr>
<tr>
<td>Relations – system entities are coupled via a form of relationship, rather than simply being aggregated (e.g. pile of sand).</td>
<td>Defining the resources of a current process as the products of a past process and the products of a current process as the resources of a future process couples adjacent systems as part of each other, rather than simply being next to each other.</td>
</tr>
<tr>
<td>Position – dynamics of system entities depend on how they are embedded in their environment as well as the history of the system as a whole.</td>
<td>The network of dynamic RTP systems depicted in 7.22 can describe the position of $S_o$ in relation to what comes before and after it by defining its linkages.</td>
</tr>
<tr>
<td>Integrity – the sum of the system entities is greater than its parts with integrated feedback loops coupling certain parts to maintain the system’s identity.</td>
<td>The RTP system is structurally divisible but functionally whole. Reinterpreting a real world system using the RTP system reinforces the integrity of the total system.</td>
</tr>
<tr>
<td>Intricate behaviour – system behaviour is poised between simple order and total disorder making its description difficult despite not being completely random.</td>
<td>As a network of RTP systems is defined, entities will appear in ‘before’ and ‘after’ system representing feedback and nonlinear processes which give rise the intricate complex behaviour.</td>
</tr>
<tr>
<td>Stability – unity of the system is preserved under small perturbations and adaptive under moderate changes in its environment.</td>
<td>By expanding the analysis to the form of Figure 7.22 and assessing the resilience and stability by applying a method similar to Ulanowicz et al. [111] the propensity of the system to sustainability can be quantified.</td>
</tr>
<tr>
<td>Observer relativity – measures and judgements about complexity depend upon the choices of the observer.</td>
<td>The RTP system boundaries, although logical, are open to the perspective of the process the analyst focuses upon.</td>
</tr>
</tbody>
</table>
7.9.3 Limitations

As will be seen in the case studies of chapters 8 and 9, the extent to which the model is quantifiable has not yet been fully explored, which limits the current value of the work. It is able to take advantage of many existing techniques in the literature, such as LCA and describing resilience and organising information for problem solving as discussed in section 7.9.2, but the models potential and distinctive characters need further definition. A process for assessing those limits and defining what is quantifiable needs to be pursued by considering the following.

Firstly, the reason for the model's need to conform to the requirements of complex system descriptions is to take advantage of complex system concepts such as alternative phase spaces and attractors. It would be very useful if the dynamic behaviour of a system represented by the model could be described in terms of these concepts amongst others. This is the key for fulfilling any quantification potential. For example, can the relationship between Rs, Tr and Pr be defined so that an RTP system can be located in a space analogous to a complex plane? In that case, a network of systems in Figure 7.22 could be mapped.

However, what would the axes represent? Some effort was expended in explaining how human and economic processes evolved from natural processes over time that create three parallel system. Each of these systems could represent an axis in three dimensional space, in which case, is it possible to describe the transformation mechanics where a plane containing two of the systems combine in a cross product to form the third? Developing suitable phase spaces to represent individual RTP systems in relation to each other would allow attractors associated with system resilience to help understand, to a significant degree, the dynamics of a large networked system. If conceptual difficulties can be overcome the model could prove to be powerful in its pursuit of assessing and developing systems for their sustainability.

7.10 Summary of the model

The ideas and concepts, floated in section 7.8 above, about comparing the rate of problem proliferation and solution implementation extend well beyond the practical limits of the work presented. However, it was the aim to investigate how such a comparison could be made and what concepts might be involved rather than deducing a conclusive answer. In
the process of developing the model for that purpose, a number of practical ideas related
to system sustainability have been described.

To begin with, an analogy built upon ‘regions of stability’ used to describe the film blowing
process (section 4.1.6) and the stability and resilience associated with describing a
sustainable industrial economy, suggested concentrating on the flow and transformation of
matter and the underlying natural processes that entails. This involved re-interpreting the
scenario as the theoretical depiction of solving a complex problem iteratively in section 7.2
and then the fundamental consideration of time in sustainability in section 7.3.

The RTP system derived from that point in section 7.4 addresses some of the
complications and challenges in sustainability work listed in chapter 2. Firstly it
incorporates time in its definition by adopting a process oriented perspective where
resources and products are considered together with the processes as part of the basic
system. Also, the scale of an analysis can be altered simply by re-defining the boundary
of the RTP system and using the same conceptual definitions of resources, Rs, processes,
Tr, and products, Pr. In using the method, the analyst is forced to consider what comes
before and what comes after, a simple tactic to expand an analysis beyond what is
immediately apparent. By linking a number of appropriate RTP systems together, material
waste can be removed from an encompassing system, and a sustainable system from a
thermodynamic perspective can be described as in Figure 7.12.

However, it is by considering the evolution of natural processes as described in section 7.5
that a sustainable system incorporating humanity can be derived. By defining the natural,
human and economic systems using the time and process concepts of section 7.3, a RTP
system on the scale of millennia can in turn be defined (section 7.6), and eventually by
combining Figures 7.17 and 7.19 a model suitable for assessing and developing a
sustainable industrial system is presented in section 7.7 and Figure 7.21. This
representation, combined with Table 7.1 is a tool that can be used to integrate a variety of
systems. For example, a sole focus on natural systems, Sn, addresses material and
energy flows of any system, such as what would be part of science and engineering. A
sole focus on human systems, Sh, addresses flows of data, information and knowledge,
such as what would be part of information technology and communications. A sole focus
on economic systems, Se, addresses flows of value and money, such as would be part of
finance and commerce. The nexus of various flows of entities from each of these systems
in the correct proportion yields the composition of entities that constitute the system being observed, \( S_0 \). It is by this understanding that the difficulties of incorporating social and cultural entities into sustainability assessments could be circumvented.

In theory, by integrating many \( S_0 \) analyses, a network of systems can be built to yield a ‘fabric’ composed of the flows and transformations of the global industrial economy, as in section 7.8. The continuity of the fabric is likened to the sustainability of the industrial economic system, while its shape and contours is likened to its development. Finally, regions of fabric stability can be identified as interactions of problems and solutions and what influences or affects those regions of stability can be studied through simulations.

The practical outcome presented here in section 7.7 is a tool for organising information derived from other sustainability assessments, metrics and indicators to assist making decisions and identifying actions for assessing and developing a system’s sustainability. Table 7.2 below provides a summary of its key concepts. Following in chapter 8, the model is demonstrated and explained further by applying it to scenarios presented in the starch based biodegradable plastic study of chapters 4-6. In chapter 9, the operation of a material reuse business is analysed using the model concepts to demonstrate a commercial application and construct a rudimentary information system.
Table 7.3: A summary of the seven principal concepts used to construct the model.

1. **Dynamics of problem/solution system**

   ![Diagram of dynamics of problem/solution system]

   The process of solving complex problems by obtaining knowledge of a system over time.

   - **Dynamics of problem/solution system**
     - \( t = 0 \)
     - \( K_n = 0 \)
     - \( [S] = [Pbm] \)
     - \( [Pbm]/[Sin] \to \infty \)
     - \( t \to \infty \)
     - \( K_n \to 1 \)
     - \( [S] = [Sin] \)
     - \( [Pbm]/[Sin] \to 0 \)

2. **Defining time**

   ![Diagram of defining time]

   A unit of time occurs via a transformative process, \( Tr \), which describes a theoretical spherical space of possible trajectories for time, \( t > 0 \).

3. **Defining monadic RTP system**

   ![Diagram of defining monadic RTP system]

   The monadic RTP system is constrained by a set of resources, \( Rs \), within which a set of processes, \( Tr \), acts to yield a set of products, \( Pr \), over time.

4. **Aggregating processes**

   ![Diagram of aggregating processes]

   Aggregating RTP units over time, cyclic material flow of a sustainable system driven by an external source of low entropy energy can be derived.
5. **Discerning natural, human and economic processes**

Concepts 2 and 3 combine to discern natural, $S_N$, human $S_H$, and economic, $S_E$, systems by type of process. $S_N$, $S_H$ and $S_E$ processes = $Rs$, $Tr$, and $Pr$, of a monadic RTP system described with an evolutionary time scale.

6. **Temporal expansion of single process system**

Extend concept 5 to organise information pertaining to a system, $S^0$, to assist in assessing and developing its sustainability. Tabulate known information of 21 sets plus process times and changes in resource utility of 7 systems.

7. **Integrate multi-system network**

$S^0$ analyses can be applied to any process system and the individual analyses combined to form a polymer like network. Existing knowledge of the network details indicate [Pbm/Sln]. The resilience and stability of the network defines the sustainability of the system.
8. Applying the model to the experimental study

This chapter presents how the model can be applied to aspects of the experimental study. The examples are not exhaustive, since that would require significantly more space to describe. They are qualitative rather than quantitative but still aim to convey the key points about defining the RTP systems for a scenario and the type of entities that comprise the natural, human and economic systems.

In Figure 8.1, the scenarios, I-IV, are associated with the four parts of the experimental study depicted in Figure 3.3. They are essentially in reverse order from the process of producing the viscosity models, scenario I; the process of plastic film production, scenario II; the flow of petrochemical based plastic packaging film in the economy, scenario III; and the flow of starch based plastic packaging film in the economy. The latter two are compared against each other as the original research problem and solution scenarios. The table lists these scenario descriptions as the system of observation, $S_{O0}$. As a starting point, the before, $S_{-1}$, and after, $S_{1}$ systems are equivalent to the natural systems, $S_{N}$, whose entities are of matter and energy.

8.1 Scenario I – Process of producing viscosity models

The ability to predict the viscosity of the thermoplastic material at the end of the extrusion process, $S_{-1}$, is for optimising the blown film process, $S_{1}$. The resources for the observed process, $[S_{O0}]-Rs$, include those of the natural system, $[S_{N-1}]-Pr$, entities of polymer feedstock and additives. They also include the extrusion equipment, slit-die rheometry equipment, the electricity and cooling water, the manpower in both physical form and energy of labour.

However, these resources are insufficient to produce the viscosity models on their own. Knowledge of how to obtain the data, provided in section 5.4, is necessary, as well as how to manipulate the data into the form of the model equation, Eq. 6.7, as described in section 6.4. These entities are parts of the human system, $[S_{H-1}]-Pr$. The other resources required for the modelling process to proceed are the finance, and the actual desire to do the work. The value associated with carrying out the process will partly determine how successful the process is. These are entities of the economic system, $[S_{E-1}]-Pr$. 
Figure 8.1: Summary of the systems of observation for the four scenarios related to the experimental study.
All of these resources combine to facilitate the process, $[S_0^0]-Tr$, of producing the viscosity models, $[S_0^0]-Pr$ presented at the end of section 6.4. The process time, $S_0^0(t)$, associated with the system was about three months. The change in resource utility over the process, $\Delta RU$, is dependent on the type of resources being considered. For example, matter and energy has been combined to form an economically unusable product (in this case), so $[S_n]-\Delta RU$ is negative. However, the information and knowledge gained means that $[S_i]-\Delta RU$ could be considered positive. The process does not produce income, but the value associated with gaining knowledge, which is the point of the research, means that $[S_e]-\Delta RU$ more likely depends on the perspective of individuals.

Overall, it can be concluded that the sustainability of the process of producing viscosity models is dependent on continued access to materials, equipment, manpower and other resources mentioned above. The process could be developed sustainably by taking advantage of the value of the knowledge produced and feeding it back into the next round of modelling experiments. If the process could produce monetary income, its sustainability would improve substantially. That, in fact, is the reason to expand the system of observation to include the entire process of plastic packaging film production as part of a commercial operation.

8.2 Scenario II – Process of producing plastic packaging film

The process of producing a plastic packaging film is typical of a business operation. Resource entities of the natural system, $S_{N^{-1}}$, are similar to that of scenario I, but include equipment needed from granulation to storing the product. The resources of space, a factory floor for example, plus greater manpower and support equipment for the business such as computer and communications equipment become necessary. A greater pool of information and knowledge, $[S_{h^{-1}}]-Pr$, including not only that needed to operate the equipment and maintain the process, but about markets, product pricing and distribution are necessary if the business process is to be sustainable.

All of these resources, $[S_0^0]-Rs$, are products of the before systems, $[S^{-1}]-Pr$, which combine in the process being observed, $[S_0^0]-Tr$, to produce products, $[S_0^0]-Pr$ and become resources of the future systems, $[S^{-1}]-Rs$. The process time, $S_0^0(t)$, for converting incoming resources into outgoing products maybe on average one month, as an example. Again, the change in resource utility can be considered for each of the three universal systems. A marketable product means the matter and energy has been combined in the
process into a useful product, so \([S_N]-\Delta RU\) for the feedstocks can be considered positive, whereas that of the energy used will be negative. However, a marketable product means it has value and will produce income which will offset the negative \([S_N]-\Delta RU\) of the energy flow. That is, the money can be used to pay the power bill. An efficient operation will want to learn about the process as it continues and feed it back into future operating procedures to strive for optimisation. In such a case, \([S_N]-\Delta RU\) is positive. A business that incorporates such an action of feedback and review of knowledge into their operation is most likely to improve its sustainability.

Any incoming or outgoing entities and the process itself can be part of a conventional LCA. The results of LCAs can be incorporated into any larger sustainability assessment of the business that not only considers material and energy entities, but also the flows of information, knowledge, value and money. Once again, an even more accurate determination of the businesses sustainability can be garnered by expanding the system being observed to include its surrounding environment.

### 8.3 Scenario III – Petrochemical based plastic packaging film in the economy

Figure 8.1 summarises the systems of observation for the problem scenario, Figure 8.1(a) and the proposed solution, Figure 8.1(b). The basic difference between the problem scenario and proposed solution is the choice of polymer and additives. That is, as discussed in section 3.4, an oil-based plastic is replaced by a starch based plastic as a means to address resource depletion and plastic waste accumulation. Table 8.1 and 8.2 provide first iteration information for the two cases.

Looking at the information provided in Table 8.1, the key problem can be quickly summarised. The formation of subterranean crude oil reserves, \(S_N^{-1}\), takes millions of years of breaking down prehistoric biomass. The concentration of biomass into hydrocarbon oil and gas reserves increases the potential use of the material and therefore \([S_N^{-1}]-\Delta RU\) is positive. The time to extract the hydrocarbons, process them into polymers, produce a plastic packaging film and for it to provide its service in the market place, \(S_{00}(t)\) is arbitrarily listed here as 2 years. This process reduces total utility of the hydrocarbon molecules, since they are manufactured into highly specialised forms for the market, and \([S_{00}]-\Delta RU\) is negative. When the film is discarded, it accumulates in the environment, since the synthetic plastic materials are foreign to the ecological processes of the
Table 8.1: Initial information regarding the problem of oil-based plastic packaging film.

<table>
<thead>
<tr>
<th></th>
<th>$S_{N}^{1}$</th>
<th>$S_{H}^{1}$</th>
<th>$S_{E}^{1}$</th>
<th>$S_{O}^{0}$</th>
<th>$S_{N}^{1}$</th>
<th>$S_{H}^{1}$</th>
<th>$S_{E}^{1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Rs$</td>
<td>- prehistoric biomass</td>
<td>- oil reserve data</td>
<td>- need for packaging film</td>
<td>- hydrocarbons</td>
<td>- plastic packaging film in environment</td>
<td>- data, information of plastic packaging film in environment</td>
<td>- no value to market</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- plastics material property data</td>
<td>- inexpensive resource</td>
<td>- plastics production knowledge</td>
<td>- capital</td>
<td>- plastic packaging film market</td>
<td>- cost of disposal to consumer</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- plastic packaging film at end of service life</td>
<td>- polymer degradation</td>
<td>- accumulation of synthetic molecules</td>
<td>- cost to litter</td>
</tr>
<tr>
<td>$Tr$</td>
<td>- crude oil reserve production</td>
<td>- plastics production research</td>
<td>- material comparisons for service in market</td>
<td>- plastic packaging film production process</td>
<td>- product in service</td>
<td>- organise information of plastic packaging film in environment</td>
<td>- dilution of value as material disperses to no future processes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- distribution of cost to individuals, companies, communities</td>
</tr>
<tr>
<td>$Pr$</td>
<td>- subterranean hydrocarbons</td>
<td>- plastics production knowledge</td>
<td>- capital</td>
<td>- plastic packaging film in environment</td>
<td>- breakdown of plastic into molecules suitable for ecosystem in biosphere</td>
<td>- knowledge of plastic materials in ecosystems</td>
<td>- value of dispersed material in environment at minimum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- plastic packaging film market</td>
<td>- plastic packaging film at end of service life</td>
<td>- final cost of plastic accumulation in environment maximum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>time, $t$</td>
<td>$&gt;10^{7}$ years</td>
<td>100 years</td>
<td>1 year</td>
<td>2 years</td>
<td>$&gt;1000$ years ?</td>
<td>continuing ?</td>
<td>continuing ?</td>
</tr>
<tr>
<td>resource utility, $\Delta RU$</td>
<td>$+ve$</td>
<td>$-ve$</td>
<td>$-ve$</td>
<td>$-ve$</td>
<td>$~0$</td>
<td>$-ve$</td>
<td>$-ve$</td>
</tr>
</tbody>
</table>
Table 8.2: Initial information regarding the proposed solution of a starch based plastic packaging film.

<table>
<thead>
<tr>
<th></th>
<th>$S_{n}^{-1}$</th>
<th>$S_{h}^{-1}$</th>
<th>$S_{e}^{-1}$</th>
<th>$S_{o}^{0}$</th>
<th>$S_{n}^{1}$</th>
<th>$S_{h}^{1}$</th>
<th>$S_{e}^{1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>• current biomass/vegetation in biosphere ecosystems</td>
<td>• starch reserve data</td>
<td>• need for packaging film</td>
<td>• starch polymers</td>
<td>• starch plastic packaging film in environment</td>
<td>• data, information of starch plastic packaging film in environment</td>
<td>• biodegraded products of value to ecosystems</td>
</tr>
<tr>
<td>T</td>
<td>• wheat plant growth</td>
<td>• starch plastics production research</td>
<td>• material comparisons</td>
<td>• starch plastic packaging film production process</td>
<td>• polymer biodegradation</td>
<td>• organise information of starch plastic packaging film in environment</td>
<td>• distribution of useful material resource to ecosystem</td>
</tr>
<tr>
<td>P</td>
<td>• carbohydrates • starch polymers</td>
<td>• starch plastics production knowledge</td>
<td>• capital</td>
<td>• plastic packaging film at end of service life</td>
<td>• breakdown of starch plastic into molecules suitable for future resources in ecosystem</td>
<td>• knowledge of starch plastic materials in ecosystems</td>
<td>• health of ecosystems maintained and therefore also value</td>
</tr>
<tr>
<td>time, $t$</td>
<td>1 year</td>
<td>40 years</td>
<td>small (?)</td>
<td>2 years</td>
<td>1 year</td>
<td>continuing ?</td>
<td>1 year</td>
</tr>
<tr>
<td>resource utility, $\Delta RU$</td>
<td>+ve</td>
<td>-ve</td>
<td>-ve</td>
<td>-ve</td>
<td>+ve</td>
<td>-ve</td>
<td>+ve</td>
</tr>
</tbody>
</table>
biosphere. That is, they have no resource utility from the perspective of future natural processes, even as they degrade to ever smaller pieces over time, and $[S_{N^{-1}}]\Delta RU$ is essentially zero. That is reflected in the extended but undetermined time in many cases, as indicated by ‘$>1000$ years ?’.

The conclusions regarding the flow of materials, $[S_{N^{-1}} \rightarrow S_0^0 \rightarrow S_{N^1}]$ is:

- $S_0^0(t) \ll S_{N^{-1}}(t)$ therefore resources are depleting.
- $S_0^0(t) \ll S_{N^1}(t)$ therefore products are accumulating rapidly.
- There is no known path from $S_{N^{-1}}$ to $S_{N^1}$ therefore there is no natural cyclic flow and material is accumulating in the biosphere.
- Utility of the resource materials decreases during manufacture as complex synthetic molecules are created from simpler ones. Although the plastics degrade and disperse over time, the form of the synthetic molecules is foreign to ecological processes of the biosphere, and therefore this dispersion cannot be reversed by life sustaining processes.
- The conclusion from these points is the process is unsustainable.

Defining the problem scenario could end at this point. However, by considering the $S_H$ and $S_E$ systems, a better assessment of the problem can be gained. For example, the science and engineering prowess to create plastic packaging film has been attained relatively quickly and proficiently, $S_{H^{-1}}(t)$ about 100 years (see section 4.1.1). Yet the information and knowledge about plastic packaging film in the environment, although increasing ($[S_{H^{-1}}]\Delta RU ‘+ve’$), it is incomplete. This compounds the sustainability problem further, since a proficient process is continuing without full knowledge of the future consequences.

Looking at the $S_E$ systems, there is a market for plastic packaging film. It does the job better and for less money in many services when compared to other materials (see sections 3.3.1, 3.3.2, and 4.1.2). It is a profitable product, therefore $S_{E^{-1}}(t)$ is very small, meaning its value is readily recognised and the process is willingly funded. A key contribution to this is the low cost of oil.

At the end of its service life, the value of the material to the market as a packaging film is lost. Disposal costs may be relatively inexpensive where waste disposal is serviced, but
dropping it on the ground is free. Disposal costs are distributed amongst individuals and companies through disposal rates or to communities where litter is collected on their behalf. This cost may be currently quite low. However, the final cost of accumulating plastic waste in the environment is unknown, since its impact on ecosystems and communities is continuing to be realised. For example, the value of tourist destinations diminishes as material waste accumulates on the beaches. The cost of synthetic molecules accumulating in food chains of ecosystems is unrealised. Therefore, $S_E'(t)$ is listed as ‘continuing?’. The value continues to be diluted as it is distributed throughout ecosystems. For example, it will be increasingly more difficult to recover the material for recycling opportunities. The value of the material proceeds to a minimum as it disperses in the environment, which corresponds to a greater final cost of rehabilitation, and $[S_E']-\Delta RU$ is negative. It can be seen here how in practice, the flow of money is counter-current to that of value.

From the above comments it can be seen that although the problems of the material flow in the natural system, $S_N$, are relatively obvious, a better idea of other details that contribute to the problem can be garnered by looking at all three systems, $S_N, S_H,$ and $S_E$.

8.4 Scenario IV – Starch based plastic packaging film in the economy
Table 8.2 provides first iteration information for the proposed solution of a starch based plastic packaging film.

The conclusions regarding the flow of materials, $[S_N^{-1} \rightarrow S_O^0 \rightarrow S_N^1]$ are:

- $S_O^0(t) \sim S_N^{-1}(t)$ therefore resource supply is in balance with production.
- $S_O^0(t) \sim S_N^1(t)$ therefore products are not accumulating.
- There are well known paths from $S_N^{-1}$ to $S_N^1$ since the biodegradation and composting of plant materials are ready resources for producing future crops. Therefore cyclic flow of materials within the biosphere occurs.
- Utility of the resource materials decreases during manufacture as molecules are directed towards a particular purpose. For example, using starch for food or energy would likely take greater advantage of the resources potential. In this case, the plastics biodegrade and disperse over time but the form of the molecules allows them to readily partake in ecological processes of the biosphere. That is, $\Delta RU-S_O^0$
is positive. Therefore this dispersion can be reversed by life sustaining processes of the ecosystem.

- The conclusion from these points is the proposed process is sustainable from a material point of view.

Again, by considering further details of the $S_H$ and $S_E$ systems further details about developing the process can be gathered.

For example, the science and engineering knowledge to create starch based plastic packaging film has been attained over a shorter time that of traditional plastics, $S_H^{-1}(t)$ in this case is about 40 years (see section 3.3.6 and 4.3). The information and knowledge about starch plastic packaging film in the environment is well known if it is assumed starch and biodegradation knowledge is well established. However, its performance as a packaging film is not so well known so information continues to be gathered. This uncertainty about the performance of starch based plastic as a packaging film is the reason for the research presented in chapters 4-6.

Looking at the $S_E$ systems, there is a market for starch based plastic packaging film. But it is unlikely to do as good a job as the oil based material, and it is difficult to compete against the low cost of oil. Its potential profit is currently limited (see section 3.3.6), therefore $S_E^{-1}(t)$ is ‘small’, compared to ‘very small’ for the oil based material. At the end of its service life, disposal costs are low, as is the case with synthetic plastic materials. Similarly, disposal costs would be distributed amongst individuals and companies through disposal rates as normal. An important point though is the final cost of accumulating plastic waste in the environment is avoided. Its impact on ecosystems and communities in the form of litter is benign. Therefore, the time for the final value and cost of the biodegraded plastic product to be distributed is equivalent to the time it takes for the material to rejoin the ecosystem. Therefore, $S_E^{-1}(t)$ is listed as ‘1 year’. And since the value is being distributed to potential degradation processes throughout ecosystems worldwide, $[S_E^{-1}] \cdot \Delta RU$ is positive.

Although the sustainability from a material point of view is easily established, by looking at the $S_H$ and $S_E$ systems, the informational and economic uncertainties highlight areas that need to be developed to make production of a starch based plastic packaging film ecologically and economically sustainable.
8.5 Summary remarks

The first thing to note is that while the model in chapter 7 was developed with sustainability in mind, implying a greater emphasis on the value of the environment, it is in fact representative of a sustainable system. By laying the foundations of the model with concepts of physical processes, it is independent of what the system is. As long as it is a process system, it is applicable. This is demonstrated by how it is possible to observe a system at the level of producing the viscosity models, which is a laboratory process with no environmental considerations required for it to continue. However, as the system of observation is expanded, it comes to incorporate human and environmental processes and ultimately its sustainability is reliant upon them.

The purpose of the above examples was to provide a brief demonstration of the model with a problem/solution scenario. In its present form it is simplistic, but it does demonstrate how the model can address the issues of system integration and scale required for measurements and assessments of sustainable systems [63, 66, 74, 77, 80, 353].

From this point, particular areas of the problem can be assessed or a solution developed by focusing upon them and changing the system of observation, So0, accordingly. For example, a next stage would be to apply the experimental study process of Figure 3.4(c) as So0 and apply the model to that. The resource and process sets of the before systems, [S⁻¹]-R and [S⁻¹]-T, and the process and product sets of the after systems, [S'[⁻¹]]-T and [S'][⁻¹]-P, were not included in the discussions of scenarios I and II for this example. However, in future iterations of gathering information, knowledge of the entities within these sets would improve the confidence with which the sustainability can be determined. The aim would be to emulate the network scenario Figure 7.22 and determine [Pbm]/[Sln] for assessing sustainability of the system with such measures as resilience [104, 107, 108, 110, 111] (see section 7.9).

The information presented here is generally qualitative, but quantities can be added as the analysis becomes more thorough. Also, the focus was on non-renewable and renewable materials, and the fuller system of energy resources, human labour, capital costs etc. were ignored. These are the types of entities that would be mentioned depending on how the scope of an investigation is defined. In fact, only enough information to fill the table on a
single page for each scenario was presented so a general idea of the model could be obtained quickly. In practice, each cell of the table could occupy pages. A fuller example of using the model to construct a simple information system for a material reuse business is provided in the next chapter.

The treatment of change in resource utility, \( \Delta RU \), in this example was simplified. A better treatment would be to adopt the exergy or emergy quantification methods discussed in section 3.2.2 [128-130]. To do so would be an extensive exercise in relation to the case study presented here, but would result in a more rigorous analysis.

Another important detail to improve the accuracy of the analysis is by treating the process time as a distribution of times, since different entities will flow through the process over different times.
9. Demonstrating the model: a business case study

There are two main reasons for choosing the example described below. Firstly, the author has firsthand experience of how the business was started, being a founding director and employee during the start-up and early operation phases. Secondly, from a natural system, SN, perspective, that is in terms of matter and energy flows, the business process is relatively simple. This will allow aspects involving the human, SH, and economic, SE, systems of the model to be discussed more simply. In particular though, it is the human system and its flow of information and knowledge that will receive the most focus. A brief of the business background and its operation are provided to begin with. It will then be described in terms of the model concepts step by step.

To demonstrate a practical outcome of this process, an information system for the business operation will be outlined to the extent that points of interest become apparent for assessing the model's validity. A full description of an information system is a significant undertaking with respect to business requirements analysis and goes beyond the purpose of this discussion. It should be kept in mind though, how the model can be applied to extend upon what is presented here.

9.1 Description of the business operation

Figure 9.1(i) provides a simple illustration of a lineal flow of materials through an economy. Figure 9.1(ii) shows how a material reuse business diverts a portion of the materials destined for landfill back into the supply chain of the economy to extend their useful service life.

The business being used for the case study is Reverse Garbage Co-operative Ltd, formed in Brisbane in November 1998 and still running today. It collects clean and non-toxic material discarded from local enterprise. Materials are diverted from landfill to inexpensive reuse opportunities, the aim being to avoid wasting materials that are still usable, as described in the section above. In this way, more is made of a material's inherent value and resource efficiency increases.
Figure 9.1: (i) A simplified lineal flow of materials from resources through the supply chain to consumers and onto landfill. (ii) Material reuse businesses divert some of the materials destined for landfill back into the supply chain and increase their useful service life.

Reverse Garbage collects an average of two tonnes of material per week, less than 0.02% of the total solid waste stream in Brisbane [356]. Different timber, metal, plastic, textile, paper and card off-cuts, computer and other electronic parts, old props from theatre companies and post exhibition or convention display materials are some general examples. Enough value exists within that ‘waste’ to maintain a sound small business capable of employing the equivalent of six or seven full time employees.

Figure 9.2 provides a material flow diagram for the warehouse operation. Most materials are collected in 240 litre wheelie bins from regular suppliers, or otherwise loaded directly onto a 2 tonne flat tray truck. In some cases materials are delivered directly to the warehouse located in the inner city area. All manner of collections constitute ‘Warehouse entry’ in Figure 9.2. The truck is unloaded at the ‘Dock’, where all materials are gathered and weighed. An approximation of volume is also noted for the materials collected in wheelie bins. From there, the materials are sorted according to their potential for reuse in the ‘Sorting area’ and priced. They are then displayed in a retail space on the ‘Sales floor’ to the general public or stored in the ‘Storage area’ depending on the amount of stock. From that point, the materials flow through the warehouse in line with customer activity to
the ‘Sales counter’ and in a few cases to the ‘Lay-by area’. Not all materials collected can be sold and these become part of the operation’s waste stream via the ‘Waste area’.

![Diagram of Reverse Garbage business operation]

Figure 9.2: Flow of materials collected for selling through the Reverse Garbage business operation.

Apart from identifying how the materials flow through the operation, it is also necessary to have an idea of the human activities that conduct, control and maintain it. They can be classified broadly into three types of tasks:

1. Directorship tasks – fiduciary duties, forming medium to long term strategies to satisfy the business objectives and solving associated problems.
2. Co-ordinator tasks – management of particular areas of daily operation, e.g. sales, resource acquisition, public relations, finance co-ordinators. Short to medium term planning.
3. Manual tasks – the actual jobs involved in fulfilling the regular business operation, e.g. truck driver, sorter, sales clerk, book keeping.

These three groups do not necessarily represent three different groups of people, merely the three types of tasks involved. Employees can fulfil one or more of these. In fact, that is the case with the business discussed here - most directors perform in all three roles, which is not uncommon for small businesses. It is important to mention these here since, as will be seen later, it is the flow of various types of information between them and the knowledge they possess that undergirds the sustainability of the business.

9.2 Describing the business using model concepts

The following sections define entities of the business operation in terms of the model concepts. As more detail is captured, it becomes possible to look at building practical applications. In this case, an illustration of constructing a rudimentary information system is presented. The model will provide a means to elicit entities important to a practical system design and create a tool that can contribute significantly to establishing and maintaining a sustainable business. Again, parts of the system will be presented only to the point where they contribute to discussing the validity and utility of the model.

9.2.1 A general approach to applying the model

The questions in Table 9.1 below provide decent starting points for ascribing entities to the sets and systems that constitute the model configuration in its various forms. A first passing of the questions in Table 9.1 can provide an initial basis for an analysis. Repeating the process can continue as details emerge and enough information can be procured to identify the key flows associated with [So\(^0\)] and consequently its disposition towards ecological and economic sustainability.
Table 9.1: Questions to assist ascribing entities to the various sets and systems of the model.

<table>
<thead>
<tr>
<th>Question</th>
<th>Model association</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What do you want to do?</td>
<td>Set of products, Pr&lt;br&gt;Part of systems [S], [S(^0)], [S(^0)]</td>
<td>Desire to produce something is a common starting point for building a system.</td>
</tr>
<tr>
<td>2. Where do you want to do it?</td>
<td>Further defines systems [S], [S(^0)] and [S(^0)].</td>
<td>Location is necessary for full description of a system.</td>
</tr>
<tr>
<td>3. How do you want to do it?</td>
<td>Set of processes, Tr&lt;br&gt;Adds to the definition of system [S(^0)]</td>
<td>Processes in all systems.</td>
</tr>
<tr>
<td>4. What do you need to do it?</td>
<td>Set of resources, Rs&lt;br&gt;Adds to the definition of [S(^0)]</td>
<td>Resources in all systems.</td>
</tr>
<tr>
<td>5. Where are you going to get that from?</td>
<td>System [S(^{-1})] in general, and set [S(^{-1})]-Pr more specifically</td>
<td>Sources of resources.</td>
</tr>
<tr>
<td>6. How does that come about?</td>
<td>Sets [S(^{-1})]-Rs and/or [S(^{-1})]-Tr</td>
<td>Further details describing sources of resources.</td>
</tr>
<tr>
<td>7. What happens to it afterwards?</td>
<td>System [S(^1)] in general</td>
<td></td>
</tr>
<tr>
<td>8. Is it matter or energy?</td>
<td>System [S(_{\text{m}})]</td>
<td></td>
</tr>
<tr>
<td>9. Is it information or knowledge?</td>
<td>System [S(_{\text{i}})]</td>
<td></td>
</tr>
<tr>
<td>11. Does it describe relative value?</td>
<td>System [S(_{\text{e}})]</td>
<td></td>
</tr>
</tbody>
</table>

9.2.2 RTP system descriptions

The simplest description is in terms of a single monadic RTP system. It is provided for the core business operation of handling materials within the warehouse in Figure 9.3 below.

Figure 9.3: A description of the core business operation in terms of the monadic RTP system.
Expanding the definition of the total system, S, another option could be as shown in Figure 9.4.

![Diagram of expanded system]

- **S** Materials discarded in the greater Brisbane city processed and sold by Reverse Garbage
- **Rs** Enterprises with reusable material discards within the greater city area
- **Tr** Material reuse business located at inner Brisbane city warehouse that collects, sorts and sells R
- **Pr** Materials being reused in customer markets

Figure 9.4: Expansion of the definition for the total system, S, to incorporate suppliers and customers.

The main difference is that the definition of the total system, S, in Figure 9.3 is equivalent to the definition of the set of processes, Tr, only, in Figure 9.4. The total system boundary has expanded from the warehouse to the greater city area. These examples illustrate the importance of maintaining definition of sets and systems when using the model. Both are correct uses of the monadic RTP system concept, but to decide what is more practical to move forward with requires knowledge of the motivation for the analysis in the first place.

As stated above, the aim of this analysis is to describe an information system *for the business*. In this case then, the focus should be on process details of the Reverse Garbage warehouse operation, rather than what is external to it, since that is what is within control of the business owners. The definition in Figure 9.4 may be more useful from a city council or local government perspective.

Yet the external systems of suppliers and customers are needed for the business to exist. Therefore, the next step is to expand the single RTP system to include these in a series of RTP systems similar to Figure 9.5.
It should be noted that the superscripts are introduced here to identify the system being observed, or of focus for the analysis, \([S^0]\), the system before it, \([S^{-1}]\) and the system after it, \([S^1]\). Theoretically it can be expanded further left to include the suppliers of the suppliers as \([S^{-2}]\), or further right to what would likely be the material disposed of in a waste system, \([S^2]\). Such an expansion might be useful to identify the stages in a life cycle assessment or something similar, but with respect to the goal of this analysis identifying these three systems with the business operation as the focus is sufficient.

### 9.3 Organising system entities as per Figure 7.21 and Table 7.1

The information important to running a business operation will change over time, particularly between the start-up or establishment phase and steady state or normal operation. The following example of organizing information according to Figure 7.21 and Table 7.1 is a first iteration from the perspective of establishing the processes. This approach will provide more angles for discussing the model application.

Rather than the single page table grid format, the content of each cell is presented under its own heading so a suggested step by step sequence of completing the table cells can be illustrated more clearly. Comments will be added at the end of steps to further clarify the process.

**Step 1:** Define \([S^0]\) – the system being observed

- The system being observed is a small business operation that collects, sorts, and sells clean, non-toxic materials discarded from local enterprise in the Brisbane city area. Its aim is to supply inexpensive materials to markets that can take advantage of their reuse.
- Ecological sustainability will primarily be determined by the operation’s contribution to resource efficiency. Resource efficiency is inversely dependent on the rate at which collected materials eventually enter the waste stream, which will decrease in proportion to the time the materials are valued in their future use.
Economic sustainability will primarily depend on the rate at which the operation can handle materials effectively.

Comments: The core operation of the business is stated with reference to resources, processes, products and a location. In addition, there are general references to how the associated material flow is predicted to impact ecologically and economically.

Step 2: Complete [So]-Pr broadly – products of the business operation

- Sale of discarded materials to consumer markets for reuse [Sn]
- Functioning operational equipment and space
- Waste materials
- Staff
- Information generated and gathered during operation [Sh]
- Increased knowledge of business
- Operating capital [Se]
- Satisfied employees, customers, suppliers

Comments: It is generally simpler (but not always) to begin with listing the set of products, [So]-Pr, since it is usually a desire to produce something that motivates observing a system for analysis. It makes sense to list the core product of the process first. In this case it belongs to the natural system, [Sn], being the sale of discarded materials. However, it could belong to [Sh] in the case of a research program or [Se] in the case of a financial business.

It should be noted not only the obvious business products of selling goods and raising revenue are listed. Other product entities such as retaining functioning business equipment and space, as well as staff, the information generated, business knowledge and those outcomes related to other forms of value (satisfied employees, customers and suppliers) are also listed. Including these becomes more obvious after referring to Figure 7.21, where [So]-Pr → [Sn1 + Sh1 + Se1]-Rs.

Again, this list is not exhaustive, but a starting point, remembering this iteration includes the start-up phase.

Step 3: Complete [So]-Tr – processes of the business operation
Comments: How the product will be produced is a logical question to ask next. $[S_0^0]$-Tr is the centre of the system and constitutes the focus of discussion following in section 9.3.2. The processes for $[S_H]$ and $[S_E]$, which are not described at this initial stage, need to be built around the core process of the business, which can be and is described in Figure 9.2.

### Step 4: Complete $[S_0^0]$-Rs broadly – resources of the business operation

- Collected material discards
- Operational equipment and space
- Consumables
- Water
- Energy
- Staff
- Information/knowledge required to start and operate business
- Start-up capital
- Revenue from sales
- Established markets
- Supplier service

Comments: These again are broad descriptions that understandably are similar to $[S_0^0]$-Pr. The list seems more like the start of a more conventional business analysis from this point of view. Materials, water, energy and staff are noted, as is the need that markets exist to support the purpose of the business. The one major difference is the inclusion of supplier service. Since the materials collected are discarded from other businesses for free, there is a value of service component dealing with the supplier rather than a monetary payment. This is why in ‘Step 2’ supplier satisfaction is stated explicitly as a product of the operation. Again, all types of resource entities are included in this list, remembering that $[S_{N^{-1}} + S_{H^{-1}} + S_{E^{-1}}]$-Pr $\rightarrow [S_0^0]$-Rs.

### Step 5 – Split $[S_0^0]$-Rs into $[S_{N^{-1}}]$-Pr, $[S_{E^{-1}}]$-Pr and $[S_{H^{-1}}]$-Pr. Add detail if possible or as necessary

- Discarded materials to collect
  - Timbers, plastics, metals, textiles, paper, card, others
Different forms – raw off-cuts, manufactured excess, samples, discarded props

- Operational equipment and space
  - Warehouse space
  - Shop fittings
  - Wheele bin
  - Truck(s) and other vehicles
  - Office, communications and computer equipment

- Consumables
  - Office stationery, printing supplies
  - Sales packaging
  - Warehouse operation – gloves, masks, cleaning equipment

- Water
- Energy
  - Electricity
  - Fuel for vehicles
  - Labour

- Staff

[Sh]-Pr

- Information/knowledge required to start and operate business
  - Business plan
  - Information needed to perform business operations
  - Skills, experience, talents of staff

[Se]-Pr

- Start-up capital
  - Initial investment – loans, savings, grants

- Revenue from sales

- Recognised markets
  - Schools, colleges, home handymen, artists, childcare, small theatre or play groups

- Supplier service
  - Enterprises able and willing to segregate useful discarded materials for collection

Comments: After identifying the required resources generally, it makes sense to pursue details of their acquisition further, since [So]-Rs won’t exist otherwise. The extra detail provided here highlights the difference between [So]-Rs and [S]-Pr. Although the sum total of entities for each is identical, the [S]-Pr set actually represents the product entities of a set of systems, since there are multiple sources from which entities are obtained to define [So]-Rs. Also note that ‘Collected material discards’ in [So]-Rs becomes ‘Discarded materials to collect’ from the perspective of [S]-Pr.
Step 6 – Split \([S_0^0]-Pr\) into \([S_N^1]-Rs\), \([S_N^1]-Rs\) and \([S_N^1]-Rs\). Add detail if possible or as necessary

<table>
<thead>
<tr>
<th>([S_N^1]-Rs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Materials sold to consumer markets for reuse</td>
</tr>
<tr>
<td>o Inexpensive materials for schools, colleges, home handymen, artists, theatre groups, childcare etc.</td>
</tr>
<tr>
<td>• Functioning operational equipment and space</td>
</tr>
<tr>
<td>o Warehouse space</td>
</tr>
<tr>
<td>o Shop fittings</td>
</tr>
<tr>
<td>o Wheelie bins</td>
</tr>
<tr>
<td>o Truck(s) and other vehicles</td>
</tr>
<tr>
<td>o Office, communications and computer equipment</td>
</tr>
<tr>
<td>• Waste materials</td>
</tr>
<tr>
<td>o Solid waste</td>
</tr>
<tr>
<td>▪ Landfill</td>
</tr>
<tr>
<td>▪ Recyclable materials</td>
</tr>
<tr>
<td>o Waste water</td>
</tr>
<tr>
<td>▪ Drainage, grey water, sewerage</td>
</tr>
<tr>
<td>o Pollutants from energy sources</td>
</tr>
<tr>
<td>▪ Vehicle exhausts</td>
</tr>
<tr>
<td>▪ Electricity generation exhausts</td>
</tr>
<tr>
<td>• Staff</td>
</tr>
<tr>
<td>([S_N^1]-Rs)</td>
</tr>
<tr>
<td>• Information gathered during operation</td>
</tr>
<tr>
<td>o Completed worksheets, logbooks, sales receipts</td>
</tr>
<tr>
<td>o Supplier and customer contact, feedback</td>
</tr>
<tr>
<td>• Knowledge gained from operation</td>
</tr>
<tr>
<td>o Ideas to improve business, what worked, what didn’t</td>
</tr>
<tr>
<td>• Promotional information</td>
</tr>
<tr>
<td>o Advertising</td>
</tr>
<tr>
<td>o Brochures</td>
</tr>
<tr>
<td>([S_N^1]-Rs)</td>
</tr>
<tr>
<td>• Revenue from sales</td>
</tr>
<tr>
<td>o Cash, cheque, credit, bartered goods and services</td>
</tr>
<tr>
<td>• Satisfied employees, customers, suppliers</td>
</tr>
<tr>
<td>o Employees value work, customers value purchases, suppliers value service</td>
</tr>
</tbody>
</table>

Comments: There are a few points to note here. ‘Operational equipment and space’ and ‘Staff’ have appeared in \([S_N^1]-Pr\), \([S_0^0]-Rs\) and \([S_0^0]-Pr\) unchanged. This suggests they are entities that are acquired and need to be maintained by internal processes. Indeed,
maintenance of fixed assets, which ‘Operational equipment and space’ represents and processes to retain staff are vital to the sustainability of a business.

Another point is the appearance of ‘Promotional information’. Advertising and brochures about the business are used to convey information about the business to potential suppliers and customers, particularly regarding the value the business offers to them. In other words, it’s marketing. It is included here since although it is produced by the business, it is not part of the material operation, but it is a necessary resource for linking to external systems.

As can be seen, there are many diverse consequences for the entities of \([S^0]-Pr\), meaning that the \([S^1]-Rs\) set represents the sum of resource entities from a set of systems.

### Step 7 – Compare \([S^1]-Pr\) with \([S^1]-Rs\) to classify entities and assess options for \([S^1]-Rs\), \([S^1]-Tr\), \([S^1]-Pr\) and \([S^1]-Tr\) where possible

<table>
<thead>
<tr>
<th>([S^N^1]-Pr)</th>
<th>([S^N^1]-Rs)</th>
</tr>
</thead>
</table>
| • Discarded materials to collect  
  ○ Timbers, plastics, metals, textiles, paper, card, others  
  ○ Different forms – raw off-cuts, manufactured excess, samples, discarded props | • Materials sold to consumer markets for reuse  
  ○ Inexpensive materials for schools, colleges, home handymen, artists, theatre groups, childcare etc. |
| • Operational equipment and space  
  ○ Warehouse space  
  ○ Shop fittings  
  ○ Wheelie bins  
  ○ Truck(s) and other vehicles  
  ○ Office, communications and computer equipment | • Functioning operational equipment and space  
  ○ Warehouse space  
  ○ Shop fittings  
  ○ Wheelie bins  
  ○ Truck(s) and other vehicles  
  ○ Office, communications and computer equipment |
| • Consumables  
  ○ Office stationery, printing supplies  
  ○ Sales packaging  
  ○ Warehouse operation – gloves, masks, ropes | • Waste materials  
  ○ Solid waste  
  ▪ Landfill  
  ▪ Recyclable materials |
| • Water | • Waste water |

\([S^N^1]-Pr\) \(\neq\) \([S^N^1]-Rs\)  
Transformation between \([S^N^1]-Pr\) and \([S^N^1]-Rs\) is goal of operation. Increase value through sorting. \(\Delta RU\) positive between collected waste and sold materials. Optimise. External to external. Focus on \([S^N^1]\) and \([S^N^1]\) process systems.

\([S^N^1]-Pr\) \(\neq\) \([S^N^1]-Rs\)  
Fixed assets need to be maintained. External becomes internal. Look at new vs 2nd hand vs build options. Assess maintenance vs no maintenance to optimise maintenance processes, function vs cost, depreciation.

\([S^N^1]-Pr\) \(\neq\) \([S^N^1]\)-Rs  
Material waste generated by operation. \(\Delta RU\) negative for consumables and other material discards from operation. Consider reducing, reusing, recycling, biodegradable options on case by case basis. External to external. Some internal reuse.

\([S^N^1]-Pr\) \(\neq\) \([S^N^1]\)-Rs  

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- **Energy**
  - Electricity
  - Fuel for vehicles
  - Labour
  - Pollutants from energy sources
  - Vehicle exhausts
  - Electricity generation exhausts

- **Staff**

<table>
<thead>
<tr>
<th>[S^{H}\textsuperscript{-1}}]-Pr</th>
<th>[S\textsuperscript{H}]-Rs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Information/knowledge required to start and operate business</strong></td>
<td><strong>Information gathered during operation</strong></td>
</tr>
<tr>
<td>- Business plan</td>
<td>- Completed worksheets, logbooks, sales receipts</td>
</tr>
<tr>
<td>- Information needed to perform business operations</td>
<td>- Supplier and customer contact, feedback</td>
</tr>
<tr>
<td>- Skills, experience, talents of staff</td>
<td>- Knowledge gained from operation</td>
</tr>
<tr>
<td>- Ideas to improve business, what worked, what didn’t</td>
<td><strong>Promotional information</strong></td>
</tr>
<tr>
<td>- Advertising</td>
<td>- Brochures</td>
</tr>
</tbody>
</table>

- [S\textsuperscript{H}]-Pr ≠ [S\textsuperscript{N}]-Rs
  - By products of energy conversion. \( \Delta RU \) negative for materials used for energy conversion.
  - Consider choice of energy sources. Fossil fuels vs renewables. External to external. Look at [S\textsuperscript{H}]-1.] Staff tire via labour. See above.

- [S\textsuperscript{H}]-Pr = [S\textsuperscript{N}]-Rs
  - Internal processes needed to retain staff

- **[S\textsuperscript{H}]-Pr**
  - Start-up capital
    - Initial investment – loans, savings, grants
  - Revenue from sales
    - Money from customers

- **[S\textsuperscript{E}]-Pr**
  - Operating capital
    - Pay creditors

- **[S\textsuperscript{E}]-Rs**
  - Start-up capital absorbed in setting up operation – fixed assets, other. Investigate best sources of [S\textsuperscript{E}]-Pr.
  - Revenue from sales
    - Money from customers

- Internal processes to convert money component of [S\textsuperscript{E}]-Pr to [S\textsuperscript{E}]-Rs. [S\textsuperscript{E}]-Pr dependent on market satisfaction. [S\textsuperscript{E}]-Rs dispersed through external via bill payments, wages. Internal re-investment.
• Established markets
  o Schools, colleges, home handymen, artists, childcare, small theatre or play groups

• Satisfied employees, customers, suppliers
  o Employees value work, customers value purchases, suppliers value service

| Transformation between \([S^E]^{-1}-Pr\) and \([S^E]^{-1}-Rs\). Operation satisfies markets and suppliers by supplying valued goods and services. Operation satisfies employees work expectations. Look at \([S^E]^{-1}\) and \([S^1]^{-1}\) process systems. |
| \([S^E]^{-1}-Pr\) | \([S^E]^{-1}-Rs\) | \([S^1]^{-1}-Pr\) | \([S^1]^{-1}-Rs\) |

| \([S^E]^{-1}-Pr\) | \([S^E]^{-1}-Rs\) | \([S^1]^{-1}-Pr\) | \([S^1]^{-1}-Rs\) |

| \([S^E]^{-1}-Pr\) | \([S^E]^{-1}-Rs\) | \([S^1]^{-1}-Pr\) | \([S^1]^{-1}-Rs\) |

| \([S^E]^{-1}-Pr\) | \([S^E]^{-1}-Rs\) | \([S^1]^{-1}-Pr\) | \([S^1]^{-1}-Rs\) |

| \([S^E]^{-1}-Pr\) | \([S^E]^{-1}-Rs\) | \([S^1]^{-1}-Pr\) | \([S^1]^{-1}-Rs\) |

Comments: Completing Table 7.1 requires information for the resource and process sets of \([S^{-1}]\) and \([S^1]\). It is here that, where possible, choices need to be made regarding where resources come from and where products go, remembering that \([S^{-1}]\) and \([S^1]\) are in fact sets of systems (see Figure 7.22), in other words, options. These choices will define \([S^{-1}]-Rs\), \([S^{-1}]-Tr\), \([S^1]-Rs\) and \([S^1]-Tr\) and consequently determine the sustainability of the business both economically and ecologically.

9.4 Considering the options for \([S^1]\) and \([S^1]\)

At this stage, that is, at start-up, the variety of entity attributes is more dispersed, since establishing the business requires incorporating entities of external systems into internal systems. Distinguishing those attributes will assist defining \([S^{-1}], [S^0]\) and \([S^1]\) for the future. Comparing \([S^{-1}]-Pr\) with \([S^1]-Rs\) helps determine if entities are ‘fixed’ or ‘variable’, ‘static’ or ‘dynamic’; if they should be considered part of ‘internal’ or ‘external’ processes with respect to \([S^0]\); and importantly, if they are within the realm of control of the business operation where decisions can be effective. Also, the three different types of currencies obviously behave differently and will entail different types of goals for decisions.

9.4.1 Within \([S_N]\)

In the \([S_N]\) system, the variable flow of collected materials transformed through sorting to sold products, \([S_N^{-1}]-Pr \neq [S_N^1]-Rs\), is the crux of the business. The materials flow from external systems of the suppliers, \([S_N^{-1}]\), gain value through the collection, sorting and sales process and onto the external systems of the customers, \([S_N^1]\). By optimising the constituents of \([S_N^{-1}]\) while accumulating those of \([S_N^1]\), the business will be granted a better opportunity of success. The information system described in the following section will address this in more detail.

\([S_N^{-1}]-Pr = [S_N^1]-Rs\) implies fixed entities and the \([S_N^{-1}]\) and \([S_N^1]\) systems of which they are part overlap. During start-up, assets need to be bought and decisions need to be made
regarding ecological and economic circumstances. On a case by case basis, decide between buying new, second-hand or building assets. Leasing an existing warehouse is likely preferable to building a new one, but conversion processes and costs need to be considered. Outfitting the warehouse operation can be achieved mainly between second-hand purchases (truck, some shop fittings) and building specific purpose fixtures (other shop fittings) which will be cheaper and serve their purpose. But a ‘free’ photocopier that is larger, heavier, slower and less versatile than a new photocopier might prolong the equipments service life, but is it worth the time and frustration of continual paper jams and poor printing?

In a later iteration of Table 7.1 after start-up, the processes for maintenance of fixed assets can be described. At that stage, $[S_{N^1}] \sim [S_N]$ indicating that the processes are incorporated into the internal structure of the operation. What was external becomes internal, $[S_0] \rightarrow [S_0] + ([S_{N^1}] \sim [S_N])$.

Where $[S_{N^1}] - Pr \neq [S_N] - Rs$ and $\Delta RU$ is positive between the two, the indication is a process producing waste. Consider reducing, reusing, recycling, biodegradable options with costs in mind. In the cases of energy and water, most choices of supply and disposal will be limited to the infrastructure servicing the location. Reusing plastic shopping bags or stock over-run paper bags for sales packaging doesn’t present a major issue. Renewable energy is instantly preferable to fossil fuel. But biodiesel produced from farm fresh peanut oil is less preferable than that produced from waste cooking oil. Soy ink may seem preferable ecologically to petroleum-based inks but is it worth the more expensive printing equipment necessary to cope with its slow-drying?

The matter and energy components of humans have been split into ‘staff’ and ‘labour’. It might seem indifferent to include staff here in this example, but this reflects the need for a sustainable business operation not to deter staff. Again, if staff are retained, what was external becomes part of the internal processes. The energy staff provide through their labour while carrying out tasks may be substituted by automation, but not in this simple example.

Generally, where there is a material flow from and to external systems, entropy of that system of flow can decrease or increase. Where it decreases, value has been added via the energy supplied through the business operation to produce saleable products. The
useful life of the material can be extended. Where that entropy increases, waste is the eventual product and options include: reducing or reusing to increase resource efficiency; recycling, renewable resources and biodegradation to promote cyclical flow. Where material flow slows to become a fixed asset, appropriate maintenance will limit the increase in entropy, prolong service life and increase resource efficiency. All of these options contribute to ecological sustainability.

9.4.2 Within $[S_H]$

While the onus is upon throughput from external for the $[S_N]$ currency, it is upon accumulation for the $[S_H]$ currency. The business plan is the starting point and the quality of its production, defined by $[S_H^{-1}]-Rs$ and $[S_H^{-1}]-Tr$, can greatly influence how efficiently and effectively a business is established. Likewise, the prior knowledge and experience brought by staff will have a direct impact. Deciding the best targets, $[S_H^{-1}]-Pr$, for promotional material will determine how many brochures avoid the gutter. But accumulating knowledge within the business by repeating the cycle of collecting and collating data generated by the operation is a sound method that will continually enhance chances of sustainability. (See section 7.1.)

9.4.3 Within $[S_E]$

During start-up, choices need to be made for obtaining initial capital. Savings, loans, grants all entail different processes to arrive at $[S_E^{-1}]-Pr$. If a loan is required, where will it come from and under what terms ($[S_E^{-1}]-Tr$)? Once the business is up and running, decisions regarding how revenue is used need to be made. After overheads are taken care of and bills are paid, how much needs to be re-invested and to do what can define parts of $[S_E^{-1}]-Tr$ and $[S_E^{-1}]-Pr$. In this case, $[S_E]$ is contemplated together with $[S_N]$ to form some of the decision-making processes included in $[S_{0^0}]$ in a later iteration.

The value component of the $[S_E]$ currency is what drives the variable component of $[S_N]$, namely the flow of collected materials through the warehouse. Interesting and obscure materials used by suppliers in manufacturing are generally not accessible to the public but become accessible through the warehouse operation. A suitable combination of quantities and price, contributing to $[S_E^{-1}]-Rs$ and $[S_E^{-1}]-Tr$, will have customers wandering about the warehouse for hours. They value the experience as well as the purchase. News spreads by word of mouth and goodwill is generated ($[S_E^{-1}]-Tr$ and $[S_E^{-1}]-Pr$). If that material
diversity, obscurity or quantity diminishes over time, so does the customer interest and with that the market.

Suppliers are often enthusiastic to segregate materials they’d rather not dump. Since the portion of the supplier waste handled by Reverse Garbage is relatively small, redirecting materials that are still interesting and usable is generally a greater motivation than any waste disposal savings. This motivation is captured in \([S_{E^{-1}}]_{-Rs}\) and \([S_{E^{-1}}]_{-Tr}\). If for some reason one day a current supplier was offered money by another business to take that discarded material instead, or if collections became sporadic or inconvenient, there would be little incentive for them to continue supplying Reverse Garbage and the flow will cease.

As well, employee satisfaction contributes to staff retention. Being aware of the processes that create value for customers, suppliers and staff and maintaining them where possible is critical to the sustainability of the business. Creating a cycle where revenue creates value which creates more revenue to create more value and so on, is the goal to improve economic sustainability.

### 9.5 Outlining an information system for the business

The information system aims to create, enhance and refine the flow of information within the business itself as well as between the business and its suppliers and customers. By identifying and incorporating useful entities, the system will increase knowledge of the business operation, efficiency and effectiveness will improve and so will its chances of success.

For this example, it is assumed the business is established so the following analysis will apply to its daily operation. The key system tools, such as worksheets and reports, will be outlined using the model principles.

Figure 9.6 below is a reconstruction of the material flow through the business operation shown in Figure 9.2 using the RTP system configuration. Firstly, it is important to note that Figure 7.21 and Table 7.1 aren’t the only formats for applying the model. Here the interest is in the flow of collected materials through the warehouse and the information associated with that. Each individual process within the total operation can be represented by a single RTP system. (The ‘N’ subscripts signify them as belonging to matter/energy processes.) This forces the analyst to make the overlap of products from one process with the
resources of a subsequent process explicit. It is a technique that helps to avoid information appearing from nowhere or reaching a dead end.

In Figure 9.6, the first number of the superscript identifies the encompassing system, while the numbers following identify individual subsystems within that. The shadow lines of \([S_{N^{-1}}]\) and \([S_N^1]\) systems are provided as a reminder of their multiplicity.

Figure 9.6: A reconstruction of Figure 9.2 using the RTP system configuration.

### 9.5.1 Identifying informational entities associated with processes

The following lists address each individual material process system, \([S_N]\), noting its product, \([S_N]\cdot\text{Pr}\), and the informational entities involved in bringing that product about.
[Sn^11] – Supplier businesses within collection region
[Sn^11]–Pr: Discarded materials to collect

[Sn^11]–Rs
• Existing supplier database records
• Materials desired
• Information for potential suppliers – brochure, advertising
• Contact and location details of potential supplier
• Feedback reports for existing suppliers
• Approaches from potential suppliers
• Suppliers not working out

[Sn^11]–Tr
• Research potential supplier of desired materials
• Contact potential supplier – cold call, follow up lead, knock on door
• Record supplier feedback
• Handle approaches from potential suppliers
• Create record in database with supplier number for new supplier
• Update supplier information

[Sn^11]–Pr
• Up to date suppliers’ information records
  o Address, contact details
  o Materials discarded
  o Bins required, collection frequency, access details
  o Notes, issues, supplier communications

Comments: The aim is to optimise [Sn^11]–Pr by controlling the number of suppliers with respect to operational capacity while sourcing the most desirable materials in appropriate quantities. Keeping supplier information current is vital for this.

[Sn^01] – Collection
[Sn^01]–Pr: Collected materials at warehouse

[Sn^01]–Rs
• ‘Truck Run’ worksheet for current date
• Truck log

[Sn^01]–Tr
• Complete ‘Truck Run’ worksheet as materials are collected
• Chalk supplier number and date on inside of bin lid, or attach details otherwise if not in bin
• Fill out log – time out, time in, kilometres, fuel purchases (litres and dollars)

[Sn^01]–Pr
• Completed ‘Truck Run’ and log book details passed to database staff
• Supplier number and date collected on bins and other

Comments: Driver collects from suppliers around the city area and completes worksheet. (See Figure 9.8 for an example of the ‘Truck Run’ worksheet.)

[Sn^02] – Dock
[Sn^02]–Pr: Bins weighed bin volume estimated

[Sn^02]–Rs
• ‘Weighing Form’
• Details chalked on bin, other
[Sn(02)]-Tr
- Complete ‘Weighing Form’
  - Record supplier number and date collected from bin, other
  - Record weights, bin volume estimate

[Sn(02)]-Pr
- Completed ‘Weighing Form’ passed to database staff

Comments: Driver unloads trucks and completes ‘Weighing Form’. (See Figure 9.9 for an example of the ‘Weighing Form’.

[Sn(03)] – Sorting
[Sn(03)]-Pr: Sorted materials organised according to potential value down to waste

[Sn(03)]-Rs
- ‘Sorting Form’
- Details chalked on bin, other
- Sorting knowledge

[Sn(03)]-Tr
- Complete ‘Sorting Form’
  - Record supplier number, date collected, date sorted
  - Record material type
  - Record comments, e.g. form of material, cleanliness of bin and materials, amount of wastage, anything extraordinary
  - Record who sorted bin
- Remove chalked details from bin once finished with

[Sn(03)]-Pr
- Completed ‘Sorting Form’ passed to database staff
- Increased sorting knowledge

Comments: Sorter completes ‘Sorting Form’ as materials are dealt with. (See Figure 9.10 for an example of the ‘Sorting Form’.

[Sn(04)] – Waste area
[Sn(04)]-Pr: Waste materials ready for collection

[Sn(04)]-Rs
- Information regarding cut off standard between saleable and waste materials
- Knowledge of recycling and landfill options
- ‘Weighing Form’

[Sn(04)]-Tr
- Record weights of waste materials on ‘Weighing Form’ or obtain weights from landfill receipt

[Sn(04)]-Pr
- Completed ‘Weighing Form’ and landfill receipts passed to database staff

Comments: Weigh and remove materials to waste area and organise according to opportunities for recycling opportunities, kerbside recycling or general waste. Occasionally take loaded truck to landfill site.

[Sn(05)] – Pricing
[Sn(05)]-Pr: Priced materials
[Sₙ⁰⁵]–Rs
- Price guide or price on sales floor
- Pricing knowledge – what is material worth?

[Sₙ⁰⁵]–Tr
- Attach price from guide
- Consult other staff if price unknown
- Change price if required, update guide

[Sₙ⁰⁵]–Pr
- Current prices attached to materials
- Updated price guide
- Increased pricing knowledge

Comments: Sorted materials are organised for pricing if needed. If materials merchandised in bulk bins with price labels, move to sales floor or storage.

[Sₙ⁰⁶] – Storage
[Sₙ⁰⁶]–Pr: Stored materials

[Sₙ⁰⁶]–Rs
- Material storage log
- Stock levels
- Merchandising plan

[Sₙ⁰⁶]–Tr
- Record details in storage log
  - Date in
  - Material description and quantity
  - Date out
- Discuss and alter merchandising plan if necessary

[Sₙ⁰⁶]–Pr
- Up to date storage log
- Adjusted merchandising plan

Comments: Move materials between sales floor and storage according to stock levels and merchandising plan.

[Sₙ⁰⁷] – Sales floor
[Sₙ⁰⁷]–Pr: Materials on sales floor

[Sₙ⁰⁷]–Rs
- Material storage log
- Stock levels
- Merchandising plan

[Sₙ⁰⁷]–Tr
- Record details in storage log
  - Date in
  - Material description and quantity
  - Date out
- Discuss and alter merchandising plan if necessary

[Sₙ⁰⁷]–Pr
- Up to date storage log
- Adjusted merchandising plan
Comments: Move materials between sales floor and storage according to stock levels and merchandising plan.

[S_{08}] – Sales counter
[S_{08}]-Pr: Sold materials

[S_{08}]-Rs
- Price of material
- Sales category of material
- Cash register codes for material categories
- ‘Sales Ideas’ log

[S_{08}]-Tr
- Enter price and category in register
- Record observations regarding popularity of different materials in ‘Sales Ideas’ log
- Record customer feedback
- Go to lay-by process if necessary

[S_{08}]-Pr
- Sales data passed to database staff
- Entries in ‘Sales Ideas’ log
- Customer feedback report

Comments: Customers exchange money for materials and engage in banter. Anyone with an idea can contribute to the ‘Sales Ideas’ log.

[S_{09}] – Lay-by area
[S_{09}]-Tr: Materials stored in lay-by area

[S_{09}]-Rs
- Lay-by log
- Label for lay-by item(s)

[S_{09}]-Tr
- Complete lay-by log
  - Date in
  - Customer details
  - Amount to pay
  - Date out
- Attach label with customer information to item(s)

[S_{09}]-Pr
- Up to date lay-by log
- Labelled item(s)

Comments: Materials customers wish to put on lay-by are segregated.

[S_{11}] – Customer markets
[S_{11}]-Pr: Materials being reused

[S_{11}]-Rs
- Information for promoting sales
- ‘Sales Ideas’ log

[S_{11}] – Tr
- Advertise, distribute brochures
- Ask customers about what materials are going to be used for and record in ‘Sales Ideas’ log
- Record customer requests for desired materials

\[S_{i1}\]–Pr
- Increased customer awareness of business
- Increased knowledge of customer markets and what materials are used for

Comments: Customers use the materials in external systems.

**[Sn]^{12} – Material waste systems**

\[Sn^{12}\]–Pr: Dependent on system chosen to deal with different types of material waste.

\[Sn^{12}\]–Rs
- Materials to get rid of – type and quantity
- Waste disposal options

\[Sn^{12}\]–Tr
- Research reuse, recycling, landfill options if necessary (e.g. cardboard reprocessed, pallets broken down for reuse)
- Contact potential waste disposal options

\[Sn^{12}\]–Pr
- Knowledge of waste system processes and products - who can take what waste where for what
- Updated list of waste disposal options
- Collection information
  - Required form and quantities for collection
  - Collection frequency

Comments: Materials processed in external solid waste systems. Options will depend on what is available at a particular location.

### 9.5.2 The flow of information

With the entities available for data collection sufficiently identified for the materials handling operation, the next step is to collate information in the form of reports. Figure 9.7 below provides a simplified picture of how this information is linked to reports, for the most part, via database queries.

The ‘Truck Run’ worksheet (Figure 9.8) collection details are based upon data existing in supplier records, (which includes their place in collection cycle based on collection frequency and location), as well any information about potential new suppliers. The driver completes the form while completing the collections and hands it and the truck log to the Resource Acquisition (RA) co-ordinator to enter into the database. In fact, all worksheets dealing with the incoming materials up to the pricing process are handled by the RA co-ordinator. Examples of the ‘Weighing Form’ and ‘Sorting Form’ are provided in Figure 9.9 and 9.10 respectively.
Figure 9.7: A schematic of the main sources of data and key reports.

Figure 9.8: An example of the ‘Truck Run’ worksheet.
A couple of features of these are worthwhile to note. Firstly, the aim is for data collection to balance time it takes to collect it with the value it can provide. Particularly with a new business venture, it is important that as much about the operation can be learnt as quickly as possible, but the priority of moving materials for income is greater. The bare minimum is included in the design to maximise learning about the materials coming into the warehouse without hindering the actual tasks at hand. Broad categories for bin volumes and material streams based on primary commodities, (which relate to reprocessing streams), with check boxes are examples of achieving this.

The second thing is that the ‘Data in’ column is an explicit reminder for the information to continue to the next stage. It represents the overlap of the products of one system with
the resources of a subsequent one. At a glance, a stray sheet found on the ground will tell you if it needs to go to database entry or if it can be filed.

The boxes below outline the content of reports pertaining directly to materials handling part of the operation. The success of the business in both economic and ecological sustainability depends on how familiar those running the business are with the materials it is handling.

There needs to be awareness of what has the potential to be tapped, what of that is most desirable in the market place, and the capacity and adaptability of the process in between. At the centre of this is the sorting procedure that converts an anomalous mass into desirable goods.

The ‘Materials report’ captures quantities and variety of incoming materials, the yield of saleable materials, as opposed to what is not, and the changes in supply that affect that. Coupling this knowledge with the ‘Collection activity report’, an idea of the efficiency of collection can be obtained.

The ‘Sales report’ captures the quality of not only the collection processes, but also reflects problems with the sorting process that will influence how the stock is merchandised. Illogical or poor sorting can inhibit effective merchandising which in turn will significantly impact sales. As such, it is important for the ‘Sales report’ to feedback to the collection and sorting processes to refine both the quantity and quality of materials available to customers.

<table>
<thead>
<tr>
<th>Materials report</th>
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<tbody>
<tr>
<td><strong>Audience:</strong></td>
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<tr>
<td><strong>Purpose:</strong></td>
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</tbody>
</table>
| **Details:**    | Mass collected in period  
|                 | No. bins collected in period  
|                 | New suppliers  
|                 | Cancelled suppliers  
|                 | New materials  
|                 | Cancelled materials  
|                 | Material variety  
|                 | Time between bin collection and sorting  
|                 | Amount and type of waste disposed of |
| **Frequency:**  | Monthly to co-ordinators, quarterly to directors |
Comments: Monthly reports to co-ordinators can make sure there are enough of the right materials being collected and assess any changes that need to be made. Also, time lags in sorting bins or increases in unusable materials or waste can be addressed.

Quarterly reports to directors can look at material flows more closely and assess possibilities of establishing spin-off businesses based on amounts and consistency of particular materials.

<table>
<thead>
<tr>
<th>Collection activity report</th>
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<tr>
<td><strong>Audience:</strong></td>
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<td><strong>Purpose:</strong></td>
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<td><strong>Details:</strong></td>
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<td><strong>Frequency:</strong></td>
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Comments: The cost of collection can be calculated in terms of time, money and pollution. The distribution of bins will impact collection efficiency. Low bin turnover can be addressed.

<table>
<thead>
<tr>
<th>Sales report</th>
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<tr>
<td><strong>Audience:</strong></td>
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<td><strong>Purpose:</strong></td>
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<td><strong>Details:</strong></td>
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<td><strong>Frequency:</strong></td>
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Comments: Monthly reports to co-ordinators can keep track of income against projections. Act on sales ideas. Gather feedback for material collection and sorting processes. Quarterly reports to directors can investigate the need for any major process changes.

<table>
<thead>
<tr>
<th>Supplier feedback report</th>
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<td><strong>Audience:</strong></td>
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<td><strong>Purpose:</strong></td>
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<td><strong>Details:</strong></td>
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The ‘Supplier feedback report’ aims to complete this optimisation procedure by maintaining good relations with suppliers. Supplying data about their discarded materials and being forthcoming about how the materials prove to be as saleable often satisfies their interest in the operation and can lead to more latitude on choosing what is put in the wheelie bins. It is again an example of recognizing the overlap of the products of one system (the suppliers) with the resources of the next (Reverse Garbage). And tailoring the products of the prior system to the resource requirements of the current system will surely enhance the sustainable position of the latter.

9.6 Summary of business case study demonstration

The first accomplishment in the case study is demonstrating the power of continually asking ‘Where is this coming from?’, and ‘Where is that going to?’ when discussing issues of sustainability. It is comparable to defining the stages in LCA \[48, 51, 53\] Those questions are a pragmatic interpretation of the monadic RTP system definition given in section 7.4. The entire business operation is planted between the answers to these questions when applied to the materials flowing from industry to landfill. Certainly, much ground could be made towards sustainable development if they were asked by everyone of their daily interactions with household items.

By focusing on the requirements of the RTP system a path from concept to function is provided in the form of a framework for organising information that can form the basis of requirements identification \[119, 120\]. That does not define a sustainable system, sustainability, or sustainable development as such, but, as shown in section 9.3.3, it prompts the right questions regarding sustainably preferable options. Comparing \([S^{-1}]\)-Pr entities with \([S^{1}]\)-Rs entities identified which options were defined by external systems to be chosen from and which represented internal systems that could be optimised by being incorporated into the warehouse operation.
Appling the model concepts to the internal material processes of the warehouse, an adequate information system could be described for controlling and maintaining the material flow from suppliers through to customer sales. Capitalising on the feedback of information through this system ties the flow in the [SN] system with that of the [SE] system and the internal processes can proceed towards more effectively and efficiently. Both worksheet and report design reflected this.

The central purpose is to increase knowledge about what materials are out there and what can be done with them. As knowledge accumulates over an appropriate amount of time, certain material flows can be identified as being consistent in quality and quantity to reveal opportunities for spin off businesses, looking long-term at what happens to materials. This is how the linkages between systems can be defined over time and resilience, and hence sustainability of the system determined [111].

Take the example of one material encountered often in collections – polymethyl methacrylate, or perspex. This versatile plastic sheeting is used extensively in sign making and the car industry, for example. The high turnover of these products produces a continual supply of perspex offcuts that are as useful to artists as they are to home builders. Like most plastics, perspex absorbs a lot of energy into its complex molecular structure, both of which are recoverable using current recycling technologies. With the right information about the local flow of perspex, this material, which lasts indefinitely in the natural environment, could instead support an entire perspex reuse/recycling industry on its own.

It is bringing some scientific data gathering type attitude towards handling information that makes such opportunities possible for a small and relatively simple business. And if realised, most certainly contribute to its sustainability in both ecological and economic terms.

Using the model in this case does not directly determine the validity of information and knowledge. But because the model can be extended to reveal points of interconnection between systems, false and misleading information is likely to appear through a kind of data reconciliation in a future iteration of the process by comparing resource, Rs, and product, Pr, entities.
Despite the simplicity of the material flow in the example discussed here, and the apparent simplicity of the model, there is still a lot of technique to consider. Above all, it is important to maintain system definitions throughout the analysis, which in some cases is easier said than done. The analyst needs to dissolve real objects into their parts to correctly ascribe entities to sets within the right system. This can be difficult. For example, human beings are split into the natural system as staff and labour being the matter and energy components, yet they represent the entire process system, \([S_H]\), and form the basis of \([S_E]\). Defining \([S_H]\) an \([S_E]\) systems particularly in \([S^{-1}]\) and \([S']\) may prove anti-intuitive to begin with.

Overall, applying the model concepts to the business scenario in this case can be regarded as a technique useful for identifying information important for assessing and developing the viability of the business operation as part of a sustainable system. Its ability to devolve a system into parts for practical outcomes has been shown in describing an information system that can contribute significantly to the ongoing success of the business in fulfilling its objectives.
10. Conclusions

The research work presented here began as an inquiry into the impact of the current methods employed by the industrial economic system on the biospheric systems that undergird it. The operation of the former is in service to the decisions humans make as part of satisfying their own needs and desires, and organising their own lives and environments. It is important to understand where the cumulative effects of those decisions stand in relation to the limits of the life-supporting processes of the biosphere, or, in other words, how sustainable the entire activity is.

A comparison of the ASX data in Table 1.1 and that of the IPCC report [3] brought forward the ideal of determining a ratio between the rate of problem proliferation and the rate of solution implementation as a possible way to assess this scenario, and consequently as a way to support making decisions that encourage sustainable development. However, the complexity of the interaction between the natural and industrial systems involved is a severe impediment to establishing the type of knowledge required. Therefore, as a strategy to circumvent a deal of this complexity, it was decided to focus upon what influences the flow and transformation of matter in the synthesis of industrial and natural systems. The hypothesis was that such knowledge of matter could in turn contribute to developing tools for the assessment and development of sustainable systems.

10.1 Assessing the problem

A review of work related to sustainable development in chapter 2, both in a general sense and more directly related to the processing and manufacturing industries, showed that interpretations of what sustainable development is, following publication of ‘Our Common Future’ [27], are numerous and diverse. Depending on the practical application and the depth of commitment, definitions range from that encompassed by the matter-referenced principles of The Natural Step, to the practical approaches of the TBL and Five Capitals models, to those of many boardroom slogans. The metrics, indicators and assessments that ensue from the definitions and principles are even more numerous and diverse, being developed often on a case by case basis for the real world situation at hand.

The choice of measurements and assessments may be beneficial for focused applications, but when they are used to supply information to decision-making processes at higher levels, for policy construction for example, it is a problem. Initiatives like the GRI that suggest a selection of indicators to report in a standard manner are useful in this respect,
but it is the ability to integrate multifarious sources of information that is of most benefit to decision-making processes. Scalable tools like the EF and LCA are useful in this respect, as demonstrated by their prevalence in many sustainability studies over the last 20 years. But making decisions benefiting sustainability will always be complicated by the disparate outlooks of numerous stakeholders involved, and the often conflicting options for solutions, a situation that a number of industry-focused software packages attempt to resolve. Overall, despite gaining a better understanding of what developing a sustainable industrial economy involves over the last 25 years, there is considerable doubt about genuine progress.

Realising substantive progress centres around better agreement on what needs to be sustained, how it should be developed, and improving the quality of information derived from measurements and assessments to enhance the efficacy of decision-making processes. Together with vigilant accountability measures, what really matters, fully implementing the decided actions, work can contribute to a more sustainable industrial economy.

10.2 Developing a solution

By way of developing a solution, the direction of research started in chapter 3 with looking at the consequences of complex systems for problem solving. Understanding of the fundamental concepts of time, space and feedback within the dynamics of complex systems can help see how to best interpret the links between subsystems and how they integrate their entities towards the emergent outcome of the total system.

In light of a discussion about the industrial economy, the presence of a minimum quantity of matter of a certain quality is a common resource for processes of subsystems throughout complex biospheric systems that sustain life. In other words, a sufficient flow of matter of a suitable quality is necessary to sustain a living system. The research therefore focused upon the problem of accumulating material waste, (which is stagnation of this flow), and learning about what influences the flow and transformation of matter in the industrial economy to see how stagnation could be eliminated. Generally, the first and second laws of thermodynamics constrain what is possible, with the first law defining the conservation of quantities during the flow and transformation of energy and matter, and the second law imposing limits on the resultant qualities of energy and material entities as they undergo processes over time. The latter is usually described as ‘an increase of system
entropy over time,’ and means that the quality of the matter and energy of a closed system decreases over time.

The high quality, or low entropy, solar energy provided by the sun to Earth’s ecosystems is generally sufficient to moderate the entropic increases associated with the natural processes that sustain life. However, the capacity of the modern industrial economy to transform natural resources to forms of matter foreign to healthy ecosystems is such that material waste now accumulates. One particularly foreign group of materials symbolic of modern industry is plastics.

Therefore, the accumulation of plastic waste was seen as a suitable problem to investigate the influences of material flow and transformation further. In fact, it enabled the investigation of influences to continue on two levels: the first, on the macroscopic level where there is a flow of resources from subterranean oil and gas deposits through the economy and back to the terrestrial environment as waste to accumulate in ecosystems; and the second, on the molecular level where the flow and transformation of matter was studied in the laboratory using plastics processing equipment and the techniques of rheology.

### 10.3 The laboratory experiments

The laboratory study of chapters 4-6 incorporated both the macroscopic and molecular levels by using starch, rather than petrochemicals, as a polymer resource to research production of a biodegradable starch based plastic packaging film. Such a product could take advantage of renewable resources rather than non-renewable ones and address the problem of plastic waste accumulation, with the polymeric molecules of the waste packaging film able to partake in Nature’s carbon cycle through biodegradation.

The system boundary for the experiments (see Figure 5.1) was from the point of choosing plasticisers and additives to combine with the starch through granulation, onto compound extrusion of the granules using a single screw extruder, then to blown film extrusion and analysis of the final thermoplastic starch film samples. Choice of materials and processing conditions was constrained by minimising cost and maximising product biodegradability. As such, native wheat starch was combined with water and glycerol as plasticisers, and other additives, TSTMP, succinic anhydride and methyl(triethoxy)silane were added in minimal amounts to improve processing and product properties without excessively
affecting biodegradability. GPC, DSC, tensile strength tests and moisture absorption tests were the main means of analysing sample properties.

Overall, the samples produced fell well short of the processing and product requirements of a plastic packaging film material. But they were all biodegradable, complying with the current Australian standard for a biodegradable and compostable plastic material [157]. The performance of the samples in terms of processing and plastic film properties increased from re-extrusion of the basic starch-water-glycerol, then with the addition of TSTMP, then the addition to that of succinic anhydride, then finally with the addition to that of methyl(triethoxy)silane to improve barrier properties.

Despite the poor plastics properties of the samples, significant value was added to the experimental study by using slit-die rheometry to measure rheological properties of five selected samples. These were chosen to reflect influences of the above additives on viscous flow properties of the thermoplastic starch samples over a range of processing temperatures and screw speeds (the latter translated into shear rate). Using a semi-empirical power law model of viscosity that incorporated temperature and shear rate, model constants were derived that yielded very good correlations, \(0.957 < R^2 < 0.981\), between the predicted viscosity and the observed viscosity for each of the five samples over the processing conditions employed. Furthermore, the influences of additive chemistry, molecular fragmentation during extrusion, and temperature and shear rate on material flow and transformation could be successfully inferred by considering the combination of GPC, DSC and tensile strength results with rheological measurements.

10.4 Constructing a model of a sustainable system

Following the analytical techniques used to investigate a technical solution to plastic waste accumulation, chapter 7 synthesised facts and theories included in chapters 3-6 into an alternative type of solution – a conceptual model. Ultimately, it found form as a tool that configures, or organises system information in a manner suitable to assess and develop sustainable systems.

The premise for a model of a sustainable system was that the system cannot accumulate material waste. It should avoid stagnation. The flow and transformation of matter must continue within the system in such a way where what may be deemed as waste by one system is a resource for another system, in a similar way to the functioning of a healthy
ecosystem. The success of the viscosity models in chapter 6 suggested the possibility of extending the rheological methods of describing material flow and transformation in the laboratory to the material flow and transformation of the industrial economy. Further still, the ability of authors to determine the influences of molecular and process parameters on bubble stability during blown film extrusion led to the prospect of being able to determine ‘regions of stability’ associated with the dynamics of problems and solutions in a potentially sustainable industrial economy. It presents an opportunity to explore how to determine the ratio between the rate of problem proliferation and rate of solution implementation based on concepts of material flow.

The problem solving process was pictured as accumulating knowledge about the encompassing complex system. Beginning with a fundamental description of time associated with processes and the space they ascribe within that system, a fundamental unit, or monad, composed of a set of resources, Rs, a set of products, Pr and the set of processes, Tr, that transforms one to the other, was derived. Coupling two RTP systems together, one a system of concentrative processes and the other a system of dispersive processes, and provided with a source of solar energy a conceptual model of a sustainable system was described.

However, a far more pragmatic and beneficial tool for problem solving was constructed by combining the monadic RTP system with the evolution of processes that has produced natural, SN, human, SH, and economic, SE, systems, each one being encompassed by the one before. The result is a universal system where the set of resource entities of the natural system is processed by the set of entities of the human system to produce the set of product entities of the economic system. The systems are distinguished by their particular currencies: energy\matter in the natural system, data\information\knowledge in the human system, and value\money in the economic system. By analysing any process system as a nexus of these three currency flows, it is possible to organise the system’s information in a configuration that assists in identifying aspects of the system that contribute to or impede those flows. The presence or absence of links between systems can be established, the system resilience parameters determined, and in turn, the sustainability of the system can be assessed or developed.

The possibility by determining the ratio between the rate of problem proliferation and the rate of solution implementation as an indication of sustainability though, requires
integrating the analysis of countless systems by the method described above into a network. In theory, a total integration could yield a conceptual ‘fabric’ composed of the three currency flows. By subjecting the fabric to various scenarios, regions of stability could be identified, the objective being similar to that of authors modelling bubble stability in the blown film process. The conjecture is that the continuity of the flow could be related to sustainability of the system, while its shape and contours could be related to its development.

10.5 Demonstrations of the model
The demonstration of applying the model in chapter 8 to parts of the experimental study highlighted the general concepts such as those associated with defining the RTP system when observing a system, $S_0$, for analysis. The RTP system on its own is of practical benefit simply by enforcing the analyst to consider ‘what comes before’ and ‘what comes after’ the system being observed at every step.

The idea of distributing human factors that would normally be associated with social or cultural sustainability objectives amongst the three systems, natural, $S_N$, human, $S_H$, and economic, $S_E$, when properly understood, can provide the benefit of more objectively incorporating social or cultural entities into analyses. This, however, was not demonstrated sufficiently with the examples of chapter 8. Instead, distributing physical beings and manpower to the natural system, $S_N$, knowledge and experience to the human system, $S_H$, and perceived value to the economic system, $S_E$, touched upon this concept.

Quantifying the change in resource utility, $\Delta RU$, over a process system needs to be investigated further to improve the determination of system sustainability. Concepts of exergy, emergy, and measurements of information and knowledge quality would contribute positively to this. This would be preferable to converting all entities to a monetary value, the change in price over a system being the simplest, but less informative means of assessing resource utility.

The greatest promise of the model lies in its ability to integrate disparate systems. The principles behind defining the monadic RTP system are simple enough to understand how this is possible. The method of organising information suggested in Figure 7.21 and Table 7.1 can achieve efficiency gains by configuring what may seem ill-connected or disparate processes, or separate sources of information, into an integrated scheme for a common
purpose. The business case study in chapter 9 was able to demonstrate how this might be performed in practice.

There are some important details that were not discussed in chapters 7-9. The first involves the fact that the processes described by the RTP systems comprise a number of different entities. Each of these can exist as part of the process system for a different period of time. This means that the time associated with the process system as a whole is more correctly represented by a time distribution. This treatment of process times will improve the accuracy of any analysis, but complicate the mathematics involved.

Another detail not mentioned explicitly that helps further understanding is that the flow of money is counter-current to all other flows. However, this can be simply handled by changing the sign of any quantities from positive to negative, or vice versa, for a more correct depiction.

10.6 Contributions to knowledge

The basic thermoplastic starch samples produced in the experimental work were unsuitable for using as a packaging film, but they do represent a first iteration in the development of biodegradable plastic products that do exist now. The greater benefit of the experimental study was the insight into concepts of material flow and transformation that prompted contemplating the larger industrial economic system and the sustainability of its operation. The idea of modelling flow to predict future behaviour and the idea of determining regions of stability for complex dynamic systems were key to pursuing the conceptual model. Gathering data and manipulating it to provide useful rheological information, amongst other analytical techniques are important components for solving complex problems. Based upon the experience here, it would be advisable where possible for those researching sustainable development issues to incorporate a significant practical problem in the work. The physical act of carrying out an entire laboratory study revealed practical details necessary for an effective system analysis and description that could otherwise be overlooked. The method pursued in this research as a whole, therefore, could provide an example of how to structure future studies into industry sustainability.

Constructing the model involved dissolving a complex system according to the principles of material flow and transformation, to produce a simple building block – the monadic RTP
system. This does not, however, preclude its ability to describe complex systems, and by using Figure 7.21 and Table 7.1 to organise a system’s information, it does in fact take advantage of system inter-relations within an encompassing system.

The method of describing a sustainable system on the premise of the natural processes associated with material flow and transformation and their evolution is unique. So are the potential advantages this technique offers in handling human entities in particular. Also, the model is universally applicable to process systems, meaning it can shift focus and emphasis between environmental, social and economic concerns, when assessing and developing the sustainability of a single industrial operation, as illustrated in the case studies of chapters 8 and 9. However, by shifting the definition of the smaller process system to ever larger systems, the model shows how the true sustainability of a process is ultimately dependent on the healthy functioning of ecosystems.

10.7 Recommendations for future work

The most practical development of future work would be in determining the best way to quantify the concept of resource utility not only for entities of the natural system, but for quality of data, information and knowledge entities of the human system. Further understanding about applying concepts such as emergy and exergy in these contexts would be advantageous. Resource utility in the economic system, on the other hand, is better understood since that is the purpose of pricing its entities.

With improved methods of quantification, the model can be applied to industrial processes at any scale and the relationships between different industrial processes can be used to integrate them for a greater understanding of the larger system. Continuing further with this thought, it is theoretically possible by integrating many, many similarly analysed observed systems, \( n \times S_0^0 \) as \( n \to \infty \), to construct a network, or fabric, composed of the flow and transformation of energy/matter, data/information/knowledge, and value/money. This fabric could be scenario tested to determine the ranges of conditions and parameters relevant to the industrial economic system which are amenable to stable and/or resilient flow. The continuity of the flow and its shapes and contours could imply alternative states of sustainable development. By studying the ratio between the rate at which problems proliferate and the rate at which solutions are implemented it could be possible to ascertain how sustainable a certain type of development is for a given system.
11. References


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