Manufacturing Complexity: An Integrative Information-Theoretic Approach

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The thesis is entirely my own work, and, except where otherwise stated, describes my own research

In loving memory of my late father, Vasile, my aunt Maria and my grandparents

To my family, with love and gratitude
To my mother, Ecaterina and my sister, Lili
To my parents in law, Rodica and Dumitru
To my husband, Radu, and my little yet so big miracles, Maria and Tudor
To God, for giving me so much

In the beginning there was information. The word came later. The transition was achieved by the development of organisms with the capacity for selectively exploiting this information in order to survive and perpetuate their kind. The raw material is information.

F.I. Dretske [Dre]

When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but have scarcely, in your thoughts, advanced to the stage of Science, whatever the matter may be.

Lord Kelvin [Kel]

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Abstract

The modern manufacturing world is characterized by ever-increased demands for flexibility in process, product ranges and dealing with customers and suppliers, whilst having to deliver reliably and at ever lower costs. Moreover, the uncertainty and variability due to customer changes and unreliable information, material and resources may reduce the predictability and controllability levels in the system. These complexity dimensions, planned and unplanned, have to be managed, in the system design and operational stages.

This thesis provides an information-theoretic framework for the definition, measurement and control of manufacturing complexity. This methodology has the ability to integrate and quantify the structural, operational and scheduling-related decision-making characteristics of manufacturing systems. The results it provides represent an objective and sound basis for making informed design and control decisions, and for prioritizing directions for improvement. This work also facilitates comparability across system layouts, operating practices, and across time periods within a given facility.

The complexity issues in a kanban manufacturing system characterized by process variability, and the relationships between them, have been identified and quantified through simulations. Based on these results, on the previous work in the area, and on case studies and analytical modelling, the thesis proposes a novel conceptual definition of manufacturing complexity. Furthermore, the thesis identifies and justifies the need for three inter-connected classes of manufacturing complexity: structural (SC), operational (OC) and scheduling-related decision-making complexity (SDMC). Conceptual definitions of the three complexity classes are provided, and the thesis makes significant advancements in the utility, meaning and measurement methodology of SC and OC.

An innovative information-theoretic measure of SDMC is proposed in the thesis. This measure integrates product, resource, operation and sequence flexibilities, and sequence-dependent set-ups. The thesis proves that this measure is applicable to single-input single-output operation systems, as well as to systems with assembly/disassembly operations. The individual and joint capabilities of SC, OC and SDMC are discussed and illustrated for several systems, and for a real complex case study.

Additional important benefits of the complexity methodology proposed in this thesis include the ability to quantify cause-effect relationships, predict system behaviour, and to identify and quantify the trade-offs between the cost of complexity and its added value, from an information-theoretic perspective. The complexity measurement methodology presented in this thesis is generic and transferable, and can be applied to any discrete-state system.

Acknowledgements

I would like to express my deepest gratitude to Dr Janet Efstathiou, my supervisor, for having touched my life in a unique, inexorable way. Having experienced her high professionalism, gentleness, wisdom, patience, reassurance, trust, tact, talent of giving whilst encouraging freedom of thought, I could not but emerge from this experience so much richer and stronger professionally, and in many other ways.

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I gratefully acknowledge that the results reported in this thesis have been developed in close relationship with two EPSRC research projects, GR/L09295 and GR/M52458. I also feel privileged and am extremely grateful that I could work with, and benefit from many of the Oxford Manufacturing System Group's industrial partners. They are John Elliot and Ashley Pullen at Rover; Chris Bell, Neil Campbell, Steve Mumford and Steve Grigg at BAE Systems; Ray Frobisher at Unilever; Rex Rozario and Paul Comer at Graphic.

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Contents

Glossary of Acronyms

BOM	Bill of Materials
CIM	Computer Integrated Manufacturing
CP	Complexity Property, applicable to Structural, Operational and Scheduling-Related Decision-Making Complexity
DEDS	Discrete Event Dynamic System
EA	Entropy Axiom
EP	Entropy Property
ERP	Enterprise Resources Planning
FMS	Flexible Manufacturing System
GAD	Gamma Distribution
IPC	Intermediate Processing Component
IT	Information Technology
JIT	Just-in-Time
MPS	Master Production Schedule
MRP	Material Requirements Planning
MRP II	Manufacturing Resources Planning
OC	Operational Complexity
SC	Structural Complexity
SDM	Scheduling-Related Decision-Making
SDMC	Scheduling-Related Decision-Making Complexity
SDMCP	Scheduling-Related Decision-Making Complexity Property
TND	Truncated Normal Distribution
TQC	Total Quality Control
TQM	Total Quality Management
WIP	Work-in-Progress

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1 Introduction

Begin at the beginning…and go on till you come to the end: then stop.
Lewis Carroll [Car]

This chapter documents the need for an analytical, integrative and systemic approach to the definition and measurement of manufacturing complexity, and states the research objectives of the thesis (Section 1.1). Section 1.2 formally defines the research questions addressed in the thesis. Section 1.3 places the work presented in this thesis into context, and Section 1.4 outlines the methods used for achieving the research objectives and answering the proposed research questions. Sections 1.5 presents the contribution of the thesis, and Section 1.6 outlines the structure of the thesis. Section 1.7 summarises the chapter.

1.1 Motivation and statement of research objectives

The modern manufacturing world is continuously facing difficult-to-overcome challenges such as coping with changes in customer demands, staying in control while offering mass customisation at low costs, or increasing the product range in order to remain competitive [ESC98, HS00, MI90, PN96, Sch96, SM02, WS94]. These constraints are propagated and amplified along the supply chains [SEF+02, Siv01]. Various approaches to address these issues include installing a new Information Technology (IT) system, increasing the levels of stock, or investing in additional resources [CH98, ESC98]. Nevertheless, without addressing the underpinning critical problems beforehand, none of these approaches is the right answer in the long term. The right information, material and money have to move through the manufacturing system at the right time [CA92, ESC98]. However, it is very difficult to know when everything is "right" in such a complex environment. Terms such as "according to the schedule", "in control" or "due dates" may have a relative and limited meaning, unless they are based on objective and accurate information

[JRD02]. Consequently, the performance measures of such a system become limited, localised, and ultimately misleading.

Achieving a thorough qualitative and quantitative understanding of the trade-offs between flexibility, complexity, and the ability to control the production systems represents a major challenge. Flexibility allows for a swift response to customer changes [AB89, Ben92, BR96, CS96, Sla88, SL02, Too96]. On the other hand, although complexity may bring benefits such as production flexibility and product customisation, if not properly controlled it could also lead to ineffective decision-making, longer lead times, unachievable plans, larger inventories, higher costs and customer dissatisfaction, i.e. to non-predictable, non-controllable and inefficient systems [BBB+94, Ber97, Cal97c, LHPG95, Sch98, Ste96]. Adding flexibility to the factory floor increases the scheduling alternatives and, hence, the decision complexity [Ben92, BR96, Sch98]. Furthermore, high levels of uncontrolled complexity lead to poor schedule stability [ESC98, FMPT96, IR94, Wie95].

In order to cope with these challenges, the schedulers or managers responsible for the operation of the facility may adopt so-called “fire fighting” practices to solve short-term problems. These practices may then become standard practice thereafter. If the complexity of the facility increases beyond control, the facility will become unpredictable and will not be able to deliver to schedule.

In attempting to increase the level of control within the facility, the planners and managers may respond in a number of ways, such as:

- Reducing the product range;
- Product modularisation;
- Re-designing the manufacturing layout to cells;
- Installing a computer-based manufacturing information system;
- Adding extra manufacturing capacity;

- Reducing the tolerance levels allowed to customer changes, and charging for exceptions;
- Reducing the scheduling horizon.

A realistic and scientific approach to identifying and assessing critical problems in manufacturing systems should have the following properties:

- Ability to identify and assess cause-effect relationships;
- Ability to provide informed, comprehensive and meaningful answers;
- Transferability, in order to ensure the regular assessment of the system, possibly using internal resources and expertise;
- Ability to predict the expected level of improvements achieved through design or control changes;
- Transparency of decisions;
- Flexibility of the solutions provided;
- Result comparability.

Although significant research work has been carried out so far to analytically investigate the manufacturing complexity and its relationship with flexibility and uncertainty [Des93, FW95, Fri96, FS02, LKJP95, Yao85, YP90], there is no unifying methodology exhibiting all the factors and characteristics listed above, and offering a straightforward answer to the questions: Where to improve and why? How to simplify? How to assess the benefits?

This thesis proposes an integrative information-theoretic approach to manufacturing complexity, with the capabilities presented above.

1.2 Research questions

The following research questions have been identified in order to achieve the objective stated in Section 1.1:

1. What are the qualitative and quantitative aspects of complexity in manufacturing;
2. How can manufacturing complexity be defined, from an objective and global perspective;
3. How can manufacturing complexity be measured;
4. How can the measurement results be used to achieve a better understanding of the system and to improve the level of predictability and control;
5. How to balance the trade-off between system flexibility and its complexity;
6. What are the relationships between resources and demand in the system;
7. What is the impact of lot sizing policies on the system's complexity;
8. How to re-design the system so that costly or non-value adding operations are minimised;
9. What improvements can be obtained by reducing and controlling the complexity in the system, and how they can be assessed.

1.3 Research context

The research work for this thesis has been carried out whilst also working on two three-year EPSRC projects. The topic of the first project was *Improving the achievability of plans and schedules by controlling reliability and complexity*. The academic collaborator on this project was the University of Swansea, with two major industrial collaborators, British Aerospace and Rover.

The second project, *The Role of Complexity in the Supply Chain and how it Inhibits Systems Integration,* was in collaboration with Cambridge University and three leading UK manufacturers (BAE Systems, Unilever, AEA Technology and their suppliers, Graphic and Alpla).

The research work has also been closely connected to related academic and industrial events. I actively participated at the first two Workshops held in the UK on Manufacturing Complexity, organised by Efstathiou at the University of Oxford [CMW96], and Frizelle at the University of Cambridge [CMW97]. The academic and industrial interest into manufacturing complexity then extended into an EPSRC-funded Manufacturing Complexity Network, initiated by Efstathiou, Frizelle and McCarthy [MCN98, MCN99, MR00, FR02]). Two international conferences were organised in 2000 and 2002 [MR00, FR02]. I also benefited from attending two Research Methodology Workshops organised by Cambridge University in 1997 and 1998 [Cal97b].

1.4 Research methodology

The results of the thesis have been defined and refined through a complex iterative process of developing and applying ideas, receiving feedback, and analysing the results. In order to address the research problem and questions identified in this thesis, we have used the following methods:

1. *Literature review*. The purpose of the literature review was to identify previous approaches to the definition, measurement and control of manufacturing complexity, to assess their benefits and drawbacks, and to confirm the need for, and the novelty of the results presented in this thesis.
2. *Simulations.* Two major simulations have been performed. The first one represents a complex simulation of a facility at Rover, and due to space constraints and its limited academic contribution is not presented in this thesis, although these results have been presented in several papers and reports for the industrial collaborator [Cal97, CEBS97b, CEBS97c, CES+99]. This simulation identified the qualitative and quantitative issues in a complex case study. The specification of the data and information requirements for building this model had a major contribution to the approach to manufacturing complexity presented in this thesis. The second simulation model was aimed to identify the qualitative and quantitative aspects of complexity and the related cause-effect relationships between material and information flows in a simple and predictable manufacturing environment, i.e. a flow-line kanban system.

Simulation allowed the assessment of the impact of various system configurations and process variability on the system performance. The results of this simulation modelling are presented in Chapter 3. The insights obtained from this work have been used in the development of the theoretical framework presented in Chapter 4.

3. *Theoretical development*. One of the biggest challenges in answering the research questions in Section 1.2 consists of finding an answer to the problem of measurement of manufacturing complexity. This was an iterative process based on knowledge accumulation rather than merely replication of previously performed research steps. The insights from simulation modelling and case study research constituted an essential input in the theory development phase. On the other hand, the theoretical concepts have been applied and refined on case study data.
4. *Software specification and engineering* was used for the design and implementation of:
   - The control logic in the case study simulation model;
   - The dynamically configurable kanban system and of its control logic;
   - The generation of a software tool for the assessment of the scheduling-related decision-making complexity.

   The research-related contribution of this phase consists of identifying, specifying and implementing the input, structural, control and output requirements of the software tools required to support the research work presented in this thesis.
5. *Case studies*. The case studies were performed within the framework of the two EPSRC projects mentioned in Section 1.3. These case studies provided invaluable opportunities for learning and receiving feedback, and a realistic and practically grounded insight into the actual issues and requirements within a wide range of representative manufacturers. These insights significantly contributed to the development, validation, and to the generic aspect of the results presented in this thesis.
6. *Result dissemination*. The results obtained were regularly presented to the industrial partners, and feedback was sought from the academic community through the publication of journal

papers, book chapters, and through their presentation at academic conferences. Several such papers include [Cal97a-c, CEBS97a-c, CESB98, CES+00, CESH01, ECB02, ECS+01, ECS02, SECH02a, SECH02b, SEF+02].

1.5 Contribution of the thesis

This thesis advances towards a generic definition and measurement of manufacturing complexity, through the following results:

- Identification and assessment of the complexity issues in a kanban flow-line system characterized by process variability.
- A conceptual and information-theoretic framework for defining classes of complexity in manufacturing.
- The definition, integration and measurement of various aspects of manufacturing such as the mapping of the product structure on the resource structure (scheduling-related decision-making complexity), the complexity of the schedule (structural complexity), or the severity of a system's deviation from the schedule (operational complexity).
- The insight that the management of flexibility adds to the overall complexity, but complexity generated by the system being in control is adding value.
- A meaningful, valid, useful and transferable methodology for measuring manufacturing complexity.

Related work to support the results presented in this thesis includes a scheduling-related decision-making complexity assessment tool that can be used by industry to better predict and control its operations. This tool has been used to generate the results presented in Chapter 5 and Chapter 6. Also, the information-theoretic (entropy) language and understanding of complexity has been transferred to major UK companies. Several examples of case studies are briefly presented in Section 6.2, focussing on the issues investigated, the benefits for industry, and the lessons learned.

1.6 Organisation of the thesis

Chapter 2 briefly reviews the major structural and operational issues in the definition, classification, layout, management and control, and measurement of modern discrete manufacturing. It also introduces the concepts used in this thesis, and identifies and assesses previous work on manufacturing complexity, mainly from an information-theoretic perspective.

Chapter 3 uses simulation to investigate the qualitative and quantitative aspects of complexity and the related cause-effect relationships between material and information flows in flow-line kanban systems, and suggests options for optimal system design in order to cope with process variability. In doing so, this chapter addresses the research questions 1, 4-7 (Section 1.2) for a simple manufacturing system.

Chapter 4 presents a novel information-theoretic, time-, control- and process-based framework for the definition, classification and measurement of manufacturing complexity. The control-related implications derived from the manufacturing complexity concept are discussed, and three classes of complexity are introduced – structural (SC), operational (OC) and scheduling-related decision-making (SDMC) complexity. A realistic and innovative analytical framework for the measurement of SDMC with the ability to integrate a significant number of flexibility classes, multiple-resource operations, and assembly or disassembly operations is proposed. Several important predictive and control capabilities of the SC, OC and SDMC are also presented.

Chapter 5 illustrates the calculation of SDMC for various simple system configurations, and the impact of simple incremental changes on various system characteristics. The scheduling-related decision-making, structural and operational complexity are then calculated for a multi-operation, multi-resource and multi-product example system. These values are then interpreted in a meaningful and innovative manner, with an emphasis on their integrative capabilities.

In Chapter 6 we first present the methodology for measuring manufacturing complexity and discuss the practical aspects involved in doing this. Then, we describe several case studies in which individual measures of complexity have been assessed. We finally illustrate the applicability and potential of the theoretical framework presented in Chapter 4 in a real case study.

Chapter 7 summarises the contributions of the thesis and proposes future research directions.

1.7 Summary

This chapter has presented the motivation for the research work presented in this thesis. The research problem and questions have been formally defined, and the context within which the work presented in this thesis has been carried out has been described. The methods used in order to define and measure manufacturing complexity have been introduced, and the contributions of the thesis have been outlined.

2 Background

Knowledge is of two kinds. We know a subject ourselves or we know where we can find information upon it.

Samuel Johnson [Joh]

This chapter reviews the major structural and operational issues in the definition, classification, layout, management and control, and measurement of modern discrete manufacturing. The literature review presented in this chapter aims to address the following questions:

1. How can a manufacturing system be defined and modelled?
2. What are the structural and operational issues in modern manufacturing systems?
3. What are the methods of control in modern manufacturing?
4. How can the performance of manufacturing systems be assessed?
5. How can the properties of manufacturing systems be inferred and controlled? Why is a systemic integrative measure of manufacturing systems required?
6. What is entropy, what is system complexity, and why entropy is a valid measure of system complexity?
7. What are the different entropic approaches to modelling and measuring complexity, and what are their strengths and limitations?

A discrete-event based definition of manufacturing systems in presented in Section 2.1, in support of the idea that a formal approach to modelling and measurement of manufacturing systems is needed. This definition is then linked with the definition of a generic manufacturing system, with the aim to answer the first question. Sections 2.2 and 2.3 provide the answer to the second question by presenting the main classes of manufacturing systems and their characteristics, and the main classes of layouts in manufacturing, respectively. Section 2.4 reviews the main methods of material and information control, pull-type systems and JIT, versus push-type systems and MRP, and thus addresses the third question. Section 2.5 introduces the main classical performance measures in manufacturing (corresponding to the fourth question), and Section 2.6 presents the analytical thinking approach, which indicates that a manufacturing system possesses a different range of properties than those obtained through summing up the properties of its components (addressing the fifth question). Section 2.7 introduces the information-theoretic concept of entropy as a measure of information, choice and uncertainty and links it to the system complexity. It therefore addresses the sixth question. Section 2.8 answers the seventh question, as it investigates and assesses previous work in developing and applying information-theoretic measures to manufacturing. Section 2.9 discusses the main issues presented in this chapter and links them with the research questions that this thesis proposes to address.

2.1 A timed Discrete Event Dynamic System (DEDS) definition of manufacturing systems

Timed DEDS are defined by means of a *stochastic timed state automaton* [BBK94, Cas93, CE96, CH90, Ho89, Ho94, RW89], i.e. a six-tuple $[\mathbf{E}, \mathbf{S}, \mathbf{E}(s), f, s_0, G]$, where:

- $\mathbf{E}$ is a discrete, possible infinite set of *events*;
- $\mathbf{S}$ is a discrete, possible infinite set of *physical states*;
- $\mathbf{E}(s)$ is a set of *feasible* or *enabled* events, defined for each state $s \in \mathbf{S}$, with $\mathbf{E}(s) \subseteq \mathbf{E}$;
- f is a *state transition* function, $f: \mathbf{S} \times \mathbf{E} \to \mathbf{S}$, defined only for $(s, e) \in \mathbf{S} \times \mathbf{E}(s)$ such that $e \in \mathbf{E}(s)$;
- $s_0 \in \mathbf{S}$ is the *initial state* of the system;
- $G = \{G_e, e \in \mathbf{E}\}$ is a set of *probability distribution functions*.

Each event $e \in \mathbf{E}(s)$ is associated a *clock value* (or residual lifetime), which represents the amount of time required until it occurs. Whenever a lifetime for event *e* is needed, a sample from G_e has to be obtained. The evolution of the system depends on the complex interactions of various discrete events, such as the arrival or the departure of a job, and the initiation or completion of a task or message. The system's state changes only at these discrete instants of time, rather than continuously. The behaviour of a typical system is graphically described in Figure 2.1; the DEDS trajectory is piecewise constant and event-driven. The sequence of piecewise constant segments represents the state sequence, and the duration of each segment represents the holding time of each state.

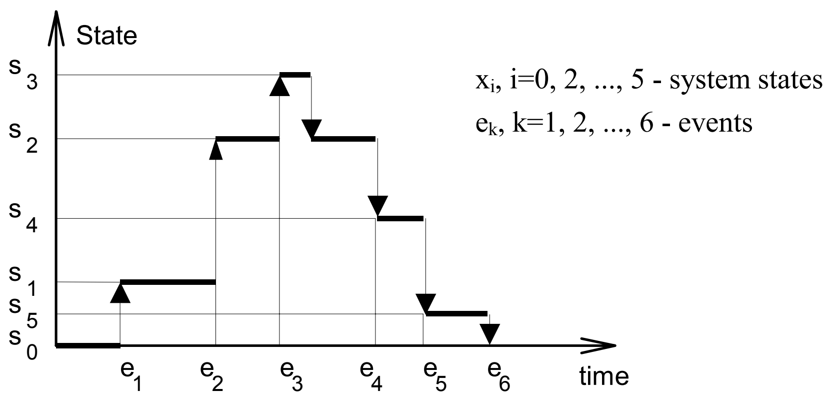

Figure 2.1 The representation of DEDS behaviour

The manufacturing systems considered in this thesis are timed discrete event dynamic systems consisting of a complex arrangement of heterogeneous physical elements characterised by measurable parameters, with various dynamic inputs, such as material, energy, demand, and social and political information, and whose main goal is to add value. The outputs, good products, good parts, information, service to customer, defectives and scrap are connected with the external customers [Bla91, Bla96] (Figure 2.2).

Benjaafar and Shantikumar [BS93] refer to any item, part, subassembly or assembly processed by a machine or work station as a *job*. They also consider that the diversity of job types manufactured by a system defines its *scope*, and the total volume of jobs defines the *scale* of the system.

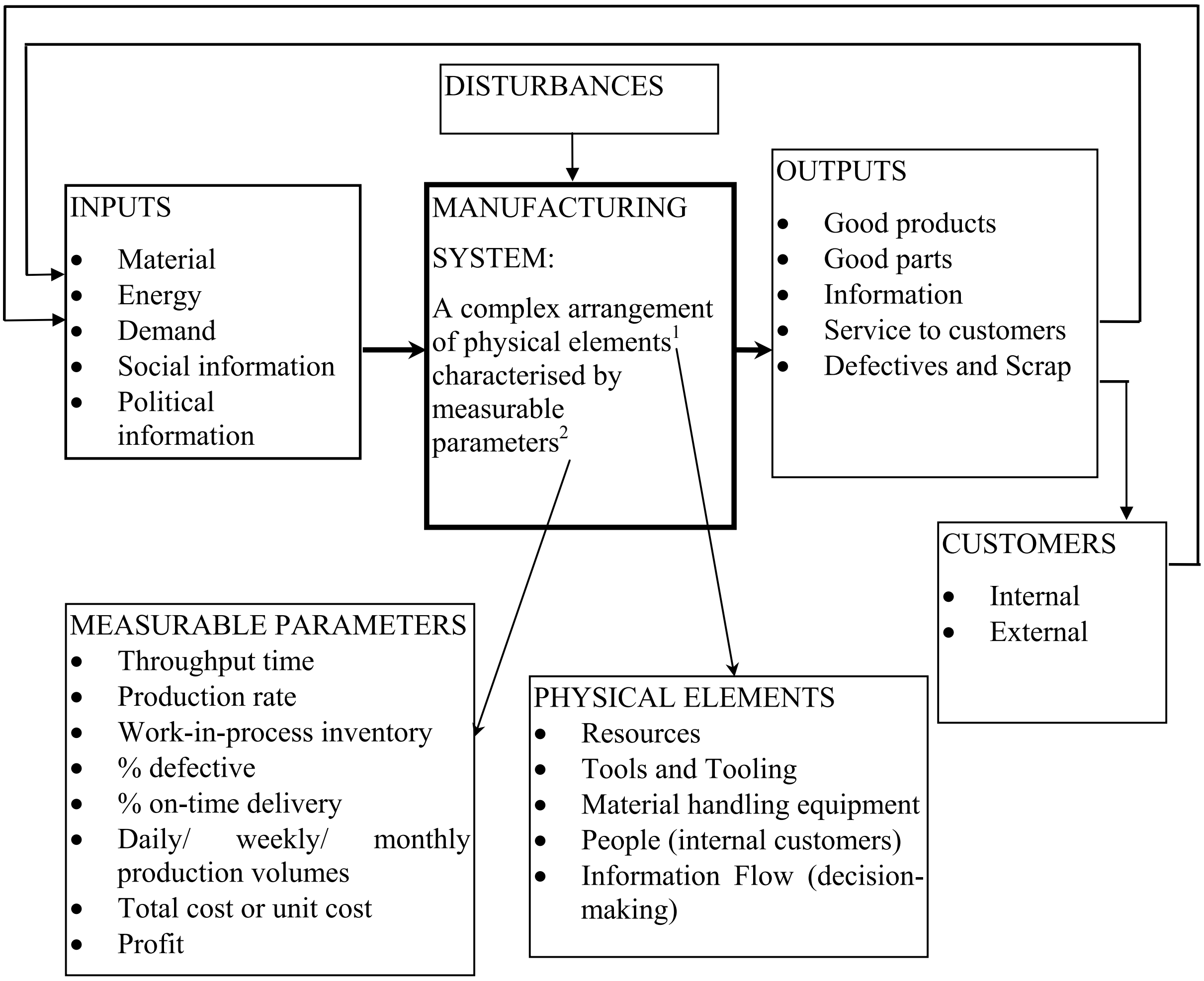

Figure 2.2 A generic manufacturing system (adapted from [Bla96])

Examples of resource-related events include information or material arrival. Examples of resource-related states include processing, waiting for information or material, set-up and breakdown. Examples of schedule-related events and states include information arrival or change, and schedule generation and execution, respectively.

2.2 Classes of Manufacturing Systems

A brief classification of manufacturing systems [BHS88, HRT96, PBH93, Sch96] is presented in Table 2.1.

Table 2.1 A classification of manufacturing systems

<table>
<tr><th>Criteria</th><th colspan="3">Classification</th></tr>
<tr><td>Type of manufacturing transformation process</td><td colspan="3">• Continuous versus Discrete
• Assembly versus Non-assembly</td></tr>
<tr><td>Volume of Production
Direction of evolution:
Flexibility increases, whilst Automation and Volume decreases</td><td colspan="3">Mass Production, usually highly automated and efficient, but inflexible (production line), characterized by “Make to Stock”, Product-flow layout
Batch Production, initially characterized by “Assemble to Order”, and followed by “Make to Order”. Flexible Manufacturing Systems (FMSs) form the most representative class of Batch Production Manufacturing. They comprise process equipment, material handling, communications, computer controls and sensors. The structure of an FMS can be either monolithic or cell-based. The features of FMSs are: manufacturing of a large variety of components, almost at random; capability to load and unload tools and work pieces automatically; capability to operate unattended for long periods. FMSs are characterized by reduced set-up and production cycle times, reduced WIP, increased machine utilisation, increased flexibility [AS93, CC96].
Jobbing shop production, characterized by “Engineer to Order”</td></tr>
<tr><td rowspan="2">Temporal Classification: Eras in Manufacturing
[Sch96], [LL02]</td><td>Classification</td><td>Period</td><td>Characteristics</td></tr>
<tr><td>Production Era
Marketing Era
Finance Era
Quality Era
Partnership Era
E-manufacturing Era</td><td>1940-50
1950-65
1965-80
1980-90
1990-
1995-</td><td>Shortages
Excess capacity, national
Concentrated earnings
Intercontinental competition
Excess capacity, global
Mass customisation, fully integrated supply chains, transparency</td></tr>
</table>

2.3 Classes of layouts

2.3.1 Flow-line systems

In the flow line layout, the jobs visit machines and work centres in the same sequence, thus simplifying the material handling and the control logic. This also limits the scope of the manufacturing system to the benefit of enabling high volumes to be produced economically [BS93].

2.3.2 Process-based systems (job shops)

Process–based systems consist of a variety of different types of machines, some of which can perform operations on different types of jobs [Ben93, BS93]. This may require set-up time between different job types. Different types of jobs can be processed by machines in a different order. This means that the material handling system must allow this. Furthermore, the same type of job could be processed on different individual machines at different times. This level of flexibility significantly increases the complexity of job scheduling, sequencing and routing. Therefore, the job shop system has scope capability, but limited ability to produce efficiently and economically [BS93].

2.3.3 Cell-based systems

The cell–based systems represent an intermediate between flow–lines and job–shop systems in terms of flexibility and complexity of the control required. A cellular manufacturing system is made up of manufacturing cells, with each cell having a specific function, scale and scope [Ang95, BS93]. The cell specifications could change as the production requirements change. Furthermore, the level of coupling between cells could vary.

2.4 Methods of material and information control

The control of manufacturing systems refers to jobs planning, off– and on–line scheduling, and monitoring. All these processes involve the interaction between material and information flow. The process of control is exercised by the production management [Bod95, BS93]. Informally, the decisions involved in management could be expressed as: Where to make?, When to make?, and How much to make? [Bod95, BS93].

The larger the scope and scale of the system, the more difficult it is to determine the answer to these questions. This difficulty is further increased by the dynamics of the system, which determine the frequency with which a decision on these issues has to be made [BS93, For61].

The production management system is a key component of the manufacturing system [BBB+94, BHS88]. According to Bauer *et al.* [BBB+94], the quality of production management can make the difference in large manufacturing facilities. While the current manufacturing environment is characterised by short product life cycles and increasing product diversity, the existing solutions to meet the challenge include techniques such as Manufacturing Resource Planning (MRP II), Just-in-Time (JIT) and Total Quality Control (TQC). They also mention that in particular the industrial managers have realised the potential of well-designed and installed production planning and control systems. On the other hand, Browne *et al.* [BHS88] emphasise that production managers, being confronted with the daily tasks and challenges, fail to address the root of the problems. This situation is also determined by the fact that conventional commercially available computer-based systems are very weak on the operational level of production planning and control [BBB+94]. On the other hand, modern manufacturing strategies are required to facilitate [BHS88, EKPW97, SL02, Too96]:

- Flexibility;
- Reduced design cycle time;
- Reduced time for marketing new products;

- Reduced order cycle time for existing products;
- High product quality;
- Co-operative value adding;

Once the desired behaviour has been achieved, sustainability (i.e. fit over time) is another desirable characteristic essentially dependent on the operations strategy [McC02, SL02]. This characteristic is linked to the emergency and adaptability properties [Che93].

Having now created an image of the issues that production management faces, the next sections will present the most important production planning and control systems, and analyse their relationships, and the pros and cons for each of them. We will also consider the manner in which the current approaches address the above questions.

2.4.1 Pull-type systems and JIT

The pull-type control is the form of control used in Just-in-Time (JIT) systems. JIT is an approach to manufacturing which concentrates on producing the required items, at the required quality, in the required quantities, and at the precise time they are required [BHS88, Har92, Sch82, SCH+95]. A key concept of JIT is simplicity, both in design and in the manufacturing process. JIT should be seen from three perspectives [BHS88, GS91, Har92, HS00, Mon93, SCH+95]:

1. The JIT philosophy or overall approach to manufacturing, i.e. eliminate waste, the involvement of everyone, and continuous improvement.
2. The techniques used within JIT to design and operate the manufacturing system, such as working practices (discipline, flexibility, equality, autonomy, line stop authority, material scheduling and data gathering), operations focus, layout and flow, total productive maintenance, set-up reduction, visibility, JIT supply, JIT planning and control techniques (kanban control, levelled scheduling, mixed modelling, and synchronization).

3. The shop floor control system of JIT, i.e. the kanban, which consists of the use of kanban cards for implementing a pull-based planning and control system. The receipt of a kanban triggers an action, such as the conveyance, production or supply, of one unit or a standard container of units, depending on the type of kanban received. Kanbans are information-carrying cards associated with containers in JIT systems [Mon93, Sch82].

The inventory level in the system is determined by the total number of kanbans, which are attached to the containers or parts, and by the container size. The optimal number of kanbans required at each stage is given by [Har92, SCH+95]:

$$n = \frac{d \times t \times (1+e)}{c}$$

Equation 2.1 The optimal number of kanbans required at each stage

where:

- n denotes the number of kanbans,
- d represents the planned average daily production for the stage, in units,
- t is the average time for machine set-up, plus the time for material handling, expressed as the proportion of the total time per day,
- $e \in [0;1]$ is a coefficient which quantifies the inefficiency of the workstation and the level of safety stock required, expressed as a proportion of the total planned production;
- c represents the unit capacity of the container.

Two kanban withdrawal policies are mentioned in the literature*: fixed withdrawal cycle - variable order quantity* (FC), in which accumulated kanbans are withdrawn at fixed intervals, and *variable withdrawal cycle - fixed order quantity* (FQ), in which the number of kanbans withdrawn is fixed [Sav96].

The systems characterised by simple product structures, which have routings with high repeatability, and high regularity in demand, are most appropriate for pull-type control. As structures and routings become more complex, and parts usages more irregular, so the effectiveness and efficiency of pull scheduling decrease. The high volume–low variety mix, while respecting the JIT principles, is considered the winning combination for JIT systems [SCH+95]. The number of containers, the number of kanbans, the relationship between the two, and the kanban withdrawal policy are important elements that determine the system's performance.

2.4.2 Push-type systems and MRP

Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRP II) are two large-scale computerised production management systems widely used in distributed, job-shop, and repetitive process manufacturing environments since the early 1970s, MRP II being an extension of MRP [BHS88, Lus93, Too96]. They were designed for dealing with dependent non-uniform customer demand and discontinuous service.

The underlying idea of MRP resides in converting a discrete plan of production for a parent item into a discrete plan of production or purchasing for its component items. MRP determines the quantity of components and materials required to fabricate the items in the Master Production Schedule (MPS), and the date when the components and materials are required. This is accomplished by exploding the Bill of Material (BOM), adjusting the inventory quantities on hand or on order, and offsetting the net requirements by the appropriate lead times. Also, being time-phased, MRP makes recommendations to reschedule open orders when due dates and need dates are not in phase.

The MRP drawbacks could be classified according to their causes into: *fundamental, behavioural* and *human-related*. All these drawbacks are inter-dependent. The fundamental MRP drawbacks refer to the assumptions MRP makes and to its structure, and include [BBB+94, BHS88, Har92, HRT96, Und94]:

- MRP models a fixed production environment
- MRP neglects the capacity and material constraints
- Lack of sufficient communication amongst its components
- Inability to capture the dynamics of modern manufacturing environments
- MRP has a complex, centralized structure, highly dependent on data accuracy, from the BOM to stock records.

Some other MRP drawbacks are related to its behaviour and to the results it provides, as Underwood [Und94] states:

- *Inaccurate Master Plans*: The MPS generally relies on forecasts, which cannot be accurate for complex systems, due to two important reasons:
    1. What is pushed into the system is not equal to what is pulled out.
    2. The system may have either higher WIP and longer lead times, or shortages.

  Therefore, the more MPS is based on forecast, the less it will match the actual demand.
- *Inaccurate inventory records*: Maintaining highly accurate records is difficult, expensive and adds cost rather than value.
- *Inaccurate lead times*: Actual lead times vary enormously according to: batch sizes, breakdown and scrap rates, or machine utilisation. As a consequence, lead times are often set longer than the optimum to ensure that the MRP system is provided with potentially accurate data. This is done at the cost of some of the benefits that the system is supposed to achieve.
- *Shortages and "hot lists"*, which represent actual customer demand or what the factory should have produced if the MRP scheduling had been correct. Although MRP is good at material planning and co-ordination, it is weak on timing, expediting and hot lists [Har92].
- *MRP nervousness*: this concept refers to the incapability of the MRP systems to deal with uncertain events. The MRP systems usually manage rescheduling, i.e., adjustment or updating

of existing schedules. However, when rescheduling takes place too frequently, the MRP system may not be able to cope with it, leading to system nervousness. Dampening methods have been used to minimise the MRP nervousness. They act as 'noise' filtering processes that remove insignificant rescheduling messages [HLR95]. Ho *et al.* [HLR95] evaluated different dampening methods usually used to solve the MRP nervousness, which included safety stock, safety lead time, safety capacity, demand management and pegged requirements.

- *Quality costs*: MRP has no way of separately monitoring quality costs such as variable yields, scrap or rework.

The human-related factors that determine the MRP's limited success include [BHS88, Har92, HRT96]: lack of top management commitment, lack of education, and lack of awareness of the importance of accurate data. These MRP drawbacks are confirmed by Braithwaite [Bra96], who provides a straightforward explanation for the MRP's success in the 1970s and 1980s and for its failure nowadays: "*Manufacturing in the 1970s and early 1908s ... was achieved by isolating manufacturing from real demand. Stable schedules, large batch sizes and long runs were the standard; product variety was condemned*". Furthermore, Higgins [HRT96] remarks that "*the MRP's core logic is only appropriate for companies with a materials management problem, not for companies that depend heavily on the proper exploitation of capacity (bottleneck) resources*". The MRP's inability to cope with the real manufacturing world has further increased with the continuous competitiveness and pressures that manufacturing currently confronts. The closed-loop MRP and MRP II are extensions of the MRP aimed to better cope with the dynamism of the real world.

Closed-loop MRP was developed to review capacity by allowing adjustments to the Master Plan, in order to make that plan attainable. It uses the logic of the MRP as well as detailed routing and capacity information from the manufacturing database. The closed-loop MRP includes the additional planning functions of sales and operations (Production Planning, MPS and Capacity Requirements Planning). Once the planning phase is complete and the plans have been accepted as realistic and attainable, the execution functions are performed. These include the manufacturing control functions of:

- input-output (capacity) measurements;
- detailed scheduling and dispatching;
- anticipated delay reports from both the plant and suppliers, and supplier scheduling.

Feedback is provided by the execution functions so that the planning can be kept valid at all times. The closed-loop MRP has been further extended by adding business and financial capabilities, reporting facilities and 'what-if' simulation capabilities [HRT96, Lus93, Too96]. The improved system was designed as an integrated approach for the effective planning of all the resources of a manufacturing company, and therefore labelled Manufacturing Resource Planning (MRP II). Output from the MRP II's functions is integrated with financial reports such as business plan, purchase commitment report, shipping budget, and inventory projections in costs. MRP II addresses the operational planning in units, and the financial planning in costs.

On the other hand, one of the main points related to the MRP systems is the fact that implementation, training, information quality and human discipline are as important as the MRP system itself [Har92, HRT96, RB92, Too96]. Therefore, certain disciplines are required to make an MRP system operate effectively, such as:

- Realistic master plans
- Inventory record accuracy
- Database integrity
- Organizational culture
- Education.

An MRP system will supply valid due dates (assuming accurate inventory and Bill of Materials), but the manufacturing system can only execute to a realistic due date. When the system is implemented and operating properly, the result will be valid and realistic plans. However, no matter how complex the production management system, the plans are worthless if they are not executed accordingly.

Enterprise Resource Planning (ERP) is designed to control all operations, i.e. manufacturing, distribution, accounting, financial and personnel. Its listed advantages include: integrated functionality, consistent user interfaces, integrated database, single vendor and contract, unified architecture and tool set, and unified product support [HS00]. The disadvantages include incompatibility with existing systems, long and expensive implementation, incompatibility with existing management practices, loss of flexibility to use tactical point systems, long product development and implementation cycles, long payback period, and lack of technological innovation.

Despite these major drawbacks, ERP has enjoyed significant success, due to its perceived applicability to Supply Chain Management and Business Process Re-engineering.

2.5 Performance measures

Performance measures are used for assessing and controlling manufacturing systems. To achieve their purpose, they should be designed and continuously updated to reflect the business's strengths and weaknesses. Moreover, their analysis should provide meaningful and straightforward directions for improvement. The performance measures could be classified according to various criteria:

- *General vs. Specific*, i.e. independent of the class of manufacturing systems vs. characteristic to a certain class of manufacturing systems;
- *Global vs. Local,* i.e. providing overall versus resource-specific measures of the system behaviour, respectively.

One of the main difficulties in complex manufacturing systems is to define the right set of performance measures, and to achieve a general consensus on them. For example, Honda company identified two classes of customers [Bla96]:

- The *internal* customers, the users of the manufacturing system, i.e., the operators
- The *external* customers, i.e. the users of the products.

Two sets of design criteria were developed, one for each type of customer. For the internal customer Honda went for design factors such as:

- safety, reliability and maintainability of the equipment;
- equipment designed to be easy to use;
- good service from the technical teams;
- input to decision making;
- no dirty, labour-intensive jobs.

For the external customer the design criteria are the right price, superior quality and reliability, attractiveness, appropriate features, and rapid delivery. This classification is confirmed by Kehoe [Keh97], who has also developed a methodology for the evaluation and audit of performance measurement systems.

Several performance measures representative for modern manufacturing include [HS00, Lan98, Lus93, VW88]:

- *Efficiency (Productivity):* represents the useful output divided by the total input. It can be calculated either as a global or as a local measure.
- *Lead time (Throughput)*: represents the time from the moment when a batch enters the shop floor to the time it leaves manufacturing as a finished part or product. The lead time within batch production systems is composed of [BBB+94, BHS88]:
    - set-up time

- process time, often less than 5% of the total lead time
- queue time, often representing in excess of 80% of the total throughput time
- transport time

Typically, the manufacturing lead time is 10 to 20 times the actual processing time [BBB+94]. A reduction in the lead time can be achieved by the use of sound operational planning and control systems. Several Shop Floor Control systems oriented towards this objective are presented in [BBB+94]. The shorter the cumulative lead time, the easier the forecasting task for both the customer and the manufacturer [Too96], and the lower the costs. Bauer *et al.* [BBB+94] also consider that advanced information technology now brings within reach the realisation of major objectives such as the reduction of manufacturing lead time to the minimum possible, and the achievement of a high level of process control. However, they also state that the application of sophisticated technology alone is unlikely to yield a durable and efficient shop-floor strategy.

- *Delivered Quality:* The ratio between the customer returns and the gross output in any given period. For example, Black [Bla96] considers that the changes implemented in the area of quality by Toyota could determine the Third Industrial Revolution. This qualitative improvement is currently referred to as either company-wide quality control (Toyota), 'lean production' (in contrast to mass production), Total Quality Control (TQC) [Sch82], Integrated Quality Control [Bla91], or Total Quality Management (TQM) [OP95, Sad95].
- *WIP/Average WIP:* The number of parts currently in the system, and the average number of parts in the system for a given period, respectively.
- *Schedule Adherence:* Quantifies to what degree the plan was achieved, in terms of number of parts, due dates, and the order in which the parts are produced. Initially designed as a measure of the customer satisfaction, the schedule adherence is sometimes used as a global indicator of the system performance. However, its appropriateness is very much dependent on the plan validity.
- *Yield:* The average number of parts produced per unit of raw material.

- *Cost:* an important measure for upper management.
- *Customer service:* measured by the ability to make promised deliveries to customers.
- *Production volume:* it can be expressed either by value or total quantity, or in terms of the mix of products produced [BS93]. This measure is dominant for low and middle level management [BS93].

An important target of manufacturing systems is not only to be able to meet demand, but also to accommodate small, short term fluctuations in demand, with the minimum level of labour. This does not necessarily imply the minimum number of machines. For example, companies operating JIT usually have some extra capacity in equipment, allowing for temporary operators when increased production is required [Har92]. White [Whi96] performed a comprehensive survey on 125 strategy-related performance measures for manufacturing. He developed a taxonomy which categorizes these measures according to competitive priority (cost, quality, flexibility, delivery reliability, or speed), data source (internal or external), data type (objective or subjective), measure reference (self-referenced or benchmark), and process orientation (process input or process outcome). His conclusion is that the largest number of measures has been proposed for the competitive priority of flexibility, and the fewest for delivery reliability.

2.6 The analytical systems (or scientific) thinking

The systems paradigm is concerned with wholes, their properties, and their hierarchical arrangement. In the systemic approach, manufacturing systems are seen as being composed of interdependent entities (agents) with holistic and integrative properties [Che93]. These properties are associated with the inherent complexity of manufacturing systems. The main concerns of systems thinking are two pairs of ideas:

- emergence and hierarchy
- communication and control.

The manner in which manufacturing systems are defined is directly related to the methods used for analysing and controlling them. Scientific approaches are often used for the design, analysis and control of manufacturing systems. However, according to Checkland, a main characteristic of science is its reductionism [Che93].

On the opposite side is the idea that at a given level of complexity there are properties characteristic of that level (emergent at that level) which are irreducible. This idea is the kernel of the concept of emergence. The debate, reductionism – versus – emergence, is a prime source of thinking that became generalized as ‘systems thinking’.

Reductionist approaches have a limited capacity to cope with complexity [Che93, FS02, JRD02, McC02]. Opposed to this, systems thinking is concerned with a holistic-based understanding of the relationships within a system and of the system parts, as the system evolves, learns and adapts.

This view on systems thinking is seen as opposed to the Operations Research (OR) Society’s official definition:

> *“The distinctive approach of OR is to develop a scientific model of the system, with which to predict and compare the outcomes of alternative decisions, strategies and controls. The purpose is to help management determine its policy and action scientifically”.*

Amongst OR’s limitations is the fact that the model developed has to be not only valid, but also quite generic. Furthermore, no single performance criterion can possibly unite within itself the myriad considerations which actually affect decisions in social systems. On the other hand, OR is focussed on the optimisation of a performance criterion for a given scenario. However, it is the fact in real life that ‘the problem’ is usually perceived as such because of the contents and details which make it unique, rather than because of the form which makes it general. This expresses the problems which still face both OR and management science as a whole as they try to extend the application of scientific methods in areas of extreme complexity.

Systems thinking is therefore an attempt to retain much of the reductionist science, but to supplement it by tackling the problem of irreducible complexity via a form of thinking based on wholes and their properties, which complements scientific reductionism. Ideally, scientific thinking should sum up the systems thinking and the analytical thinking.

Checkland [Che93] considers that:

> "*The designer of a plant should be a 'system thinker'! He should consider not only the individual components which make up the plant, but also, at a different level of consideration, the plant as a whole whose overall performance has to be controlled to produce the required product at the required rate, cost and characteristics. He will have to ensure that there exist means by which information about the state of the process can be obtained and used to initiate action to control the reaction within predefined limits. Hopefully, by knowing the variability of the starting materials and the possible environmental disturbances to which the process will be subject, it will be possible to manipulate automatically a few control variables according to a control strategy for the plant as a whole*" [Che93].

In any hierarchy of open systems, maintenance of the hierarchy will entail a set of processes in which there is *communication of information for purposes of regulation or control.* Cybernetics provides a link between control mechanisms studied in natural systems and those engineered in man–made systems [Ash56, Wie61]. Cybernetics considers that all control processes depend upon communication, upon a flow of information in the form of instructions or constraints, a flow that may be automatic or manual. Ashby's Law of Requisite Variety [Ash56, Che93] states that:

> "*Continuing effective control in a changing environment requires a controller with a variety of response which can match the variety of the environmental information".*

2.7 Entropy as a measure of information, choice and uncertainty

From the classical thermodynamic perspective, entropy is defined as a measure of the disbalance of energy in a system or a measure of the mechanical work that the system could do. The rise of thermodynamic entropy happens automatically, i.e. other things being equal, entropy tends to its maximum [Bee94]. The thermodynamic entropy is interpreted as the natural 'force' which carries a system from an improbable to a probable condition.

From an information-theoretic perspective, entropy is defined as the amount of information required to describe the state of the system [Bee94, Cov91, Gel94, Sha48]. Entropy increases with an increase in the variety and uncertainty in the system. A system gaining in (information-theoretic) entropy is also losing information.

The complexity of a system increases with increasing levels of disorder and uncertainty. Therefore, a higher complexity system requires a larger amount of information to describe its state [CES+00, ETS+99]. Hence, an increase in the complexity of a system, through increased disorder, variety and uncertainty, will increase its entropy, which can be measured as an increase in the amount of information required to describe the state of the system.

Shannon [Sha48] was the first to introduce in 1948 the concept of measuring the quantity of information by the means of entropy, within his seminal work on a first ever mathematical theory of information, or general theory of communication.

Definition. Given a group of events $E = \{e_1, e_2, \ldots, e_n\}$ and the *a priori* probabilities of the event occurrences $P = \{p_1, p_2, \ldots, p_n\}$, where $p_i \geq 0$ and $\sum_{i=1}^{n} p_i = 1$, the entropy function is defined as:

$$H = -C \sum_{i=1}^{n} p_i \log p_i \text{, with } \log 0 = 0.$$

Equation 2.2 The information-theoretic definition of entropy

The entropy H defined by Equation 2.2 represents the only function that simultaneously satisfies the axioms EA1-EA5 below [App96, Ash65, Cov91, KE92, Sha48]:

EA1. $H = 0$ if and only if all the p_i but one are zero, this one having the value unity. Thus only when we are certain of the outcome, will the entropy be null.

EA2. If all p_i are equal $p_i = \frac{1}{n}$, then H is a monotonically increasing function of n. This means that with equally likely events there is more choice, or uncertainty, when there are more possible events.

EA3. H achieves its maximum, $\log n$ (for $C = 1$), when all the events have equal probability $p_1 = p_2 = ... = p_n = \frac{1}{n}$. This situation corresponds to maximum uncertainty.

EA4. H does not change if an additional event e_{n+1} is included in the system, with $p_{n+1} = 0$.

EA5. If any choice is broken down in several successive choices, the original H should be the weighted sum of the individual values of H (The generalized grouping axiom):

$$H\left(p_1,...,p_{r_1};p_{r_1+1},...,p_{r_2};...;p_{r_{k-1}+1},...,p_{r_k}\right) = H\left(p_1+...+p_{r_1};p_{r_1+1}+...+p_{r_2};...;p_{r_{k-1}+1}+...+p_{r_k}\right)$$
$$+\sum_{i=1}^{k}\left(p_{r_{i-1}+1}+...+p_{r_i}\right)H\left(\frac{p_{r_{i-1}+1}}{\sum_{j=r_{i-1}+1}^{r_i} p_j},...,\frac{p_{r_i}}{\sum_{j=r_{i-1}+1}^{r_i} p_j}\right)$$
$$\left(r = 1,2,...,M-1\right)$$

Equation 2.3 The generalized grouping axiom

In particular, if a choice is broken down in two successive choices, the original H will be the weighted sum of the individual values of H. This means that:

$$H\left(\frac{1}{2};\frac{1}{3},\frac{1}{6}\right) = H\left(\frac{1}{2},\frac{1}{2}\right) + \frac{1}{2}H\left(\frac{1}{3},\frac{1}{6}\right)$$

Several additional important properties of the entropy include:

EP1. H is a continuous function of p_i, $i = \overline{1,n}$. This ensures that a small change in the values of p_i will determine a small change in *H*.

EP2. H is differentiable with respect to p_i, $i = \overline{1,n}$. This property is useful for optimization purposes.

EP3. H is a concave function of p_i, $i = \overline{1,n}$. This property ensures that a local maximum is also a global maximum.

EP4. $H\left(\frac{1}{nl},....,\frac{1}{nl}\right) = H\left(\frac{1}{n},....,\frac{1}{n}\right) + H\left(\frac{1}{l},....,\frac{1}{l}\right), n,l \in \mathbf{N}^+$.

EP5. The use of 2 as the base for the logarithm in the entropy formula gives entropy the dimension of a binary digit (bit).

EP6. Any change towards equalization of the probabilities $p_1, p_2, ..., p_n$ increases H.

The bit represents an answer, "0" or "1," "yes" or "no," "on" or "off" to a single unambiguous question. The definition of the entropy is based on the idea that less-likely events are more informative than more-likely ones [Ash56, Bee94, Sha48]. A system gaining in entropy is also losing information. A system with entropy of 10 bits has a variety of 2^{10}, which equals 1024 possible alternatives. The use of the logarithm in the definition of the entropy provides a basis for counting, and therefore the important properties of a measure presented above. The information content of an event *e* with probability *p* is $H = \log_2 \frac{1}{p} = -\log_2 p$. The total entropy is obtained by weighting the information content corresponding with each event with its associated probability.

Dretske ([Dre99], p. viii) remarked:

> *"The theory of information as developed by Shannon provides a measure of how much information is to be associated with a given state of affairs and, in turn, a measure for how much of this information is transmitted to, and thus available, at other points. The theory is*

> *purely quantitative. It deals with amounts of information, not, except indirectly and by implication, with the information that comes in those amounts."*

Checkland ([Che93], p. 89) also stated:

> *"What is measured under the name of 'information' in information theory actually bears very little relation to what it is usually understood by the word in everyday language. The engineers' concern is for the efficiency of the process whereby a message – any message – becomes a signal which is transmitted and received. They are not concerned, as engineers, with the content of the message, hence the limitations of 'information' in statistical information theory, which applies to both significant and trivial messages".*

Although Dretske's and Checkland's remarks on entropy are true (Section 2.7), these are not necessarily limitations when coming to using entropy as a measure of system complexity. The properties of entropy, plus the fact that a system's entropy represents the amount of information required to describe and control the state of the system, render it equivalent to the system complexity (as proved by Efstathiou *et al.* [CES+00, ETS+99]). The comments made by Dretske and Checkland could be addressed by assigning costs and value to information, which would be related and dependent on information quality, relevance and timeliness.

2.8 Information-theoretic approaches to manufacturing complexity

So far, there have been a limited number of cases of using entropy for assessing, comparing or controlling manufacturing systems. In this section we present and compare five approaches:

1. Deshmukh's static complexity [Des93, DTB92, DTB98];
2. Frizelle's structural and operational complexity [Fri95, Fri98, FS01, FW95];
3. Karp & Ronen's entropy-based approach to lot sizing [KR92, KR94];
4. Yao's routing flexibility Yao [Yao85, YP90];
5. Sharit's use of entropic measures of entropy in evaluating human supervisory control [Sha87].

This section presents an overview and evaluation of the manner in which several entropy-based measures have been defined and used in manufacturing. On the basis of the criteria that a manufacturing measurement and control solution should fulfil (as established in Section 1.1), we define several criteria for the assessment of entropic measures of manufacturing complexity, and group them into two classes: theoretical and practical. These are listed in Table 2.2. Sections 2.8.1 and 2.8.2 compare the measures against the theoretical and practical criteria.

Table 2.2 Criteria for comparing measures of manufacturing complexity

Theoretical Criteria	Practical Criteria
Entropy-based formula used	Methodology
Theoretical development	Domain of application
Entropy embedded or associated	Aims in applying the method
Assumptions made	Interpretation of results and meaningfulness
Degree of specificity or generality	Usefulness
Capability of generalisation	Validity

2.8.1 Theoretical issues

2.8.1.1 Deshmukh's static complexity

Deshmukh, Talavage and Barash [Des93, DTB92, DTB98] developed an entropy-based analytical framework for assessing the static complexity of manufacturing systems. The manufacturing environment they considered represents a discrete parts manufacturing system, with multiple part types being machined or formed in the system simultaneously. Static complexity in manufacturing systems is a function of the structure of the system, the variety of sub-systems, and strengths of interactions.

Specifically, according to Deshmukh, Talavage and Barash, a static complexity metric must satisfy the following conditions:

- Static complexity should increase with the number of parts, number of machines and number of operations required to process the part mix.
- Static complexity should increase with increase in sequence flexibility for the parts in the production batch.
- Static complexity should increase as sharing of resources by parts increases.
- If the original part mix is split into two or more groups, then the complexity of processing should remain constant.

Thus, static complexity can be considered to be a measure of the information needed to describe the system and its components. This definition implicitly considers all the components of a manufacturing system required to make the selected set of parts. On the basis of Shannon's results [Sha48], Deshmukh, Talavage and Barash developed a formula for static complexity that satisfies all the conditions mentioned above. This formula is given by:

$$H = -\mathrm{C}\sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{k=1}^{r}\sum_{l=1}^{n}\tilde{\pi}_{ijkl}\log\tilde{\pi}_{ijkl}$$

Equation 2.4 The static complexity in the Deshmukh, Talavage and Barash approach

The meaning of the terms in Equation 2.4 is as follows.

- C represents a positive constant corresponding to the unit of measure;
- m represents the total number of operations associated with a part mix;
- n represents the number of parts to be concurrently produced in the manufacturing system;
- r represents the total number of machines associated with a given part set;
- $\tilde{\mathbf{\Pi}} = \left\{\tilde{\pi}_{ijkl}, \forall i = \overline{1,m}\ , \forall j = \overline{1,m}, \forall k = \overline{1,r}\ , \forall l = \overline{1,n}\right\}$ represent the normalized set of processing requirements, with $\sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{k=1}^{r}\sum_{l=1}^{n}\tilde{\pi}_{ijkl} = 1$.

The elements of $\tilde{\mathbf{\Pi}}$ are derived as a function of:

- The part mix and their corresponding quantities to be produced in the manufacturing system during a given schedule horizon;
- The operational requirements for each part, i.e. the resources and the sequence in which they are required and the processing times on each of them;
- The degree of interaction among parts, that is the similarity of sequences and the sharing of machines from those sequences.

According to Deshmukh *et al*. [DTB98], all the information required for assessing the static complexity is available from the production order and process plans for individual parts. The variation in static complexity is studied with respect to part similarity, system size, and product design changes. This representation accommodates multiple part types, each having multiple operations and more than one processing machine option per operation.

The Deshmukh measure is limited to machining or forming operations, where there is no aggregation or disaggregation of parts as they are processed in the system. However, the authors mention that their proposed measure can be extended to include multiple part precedences, to model assembly/disassembly operations, or to study the costs associated with increasing static complexity with respect to different cost structures for the elements of static complexity.

Deshmukh's entropy measure for static complexity is an aggregate indicator of routing, process, and product flexibility related to a set of parts. Static complexity measures the total number of decisions that are related to a part mix and hence, can be considered as an aggregate indicator of these classes of flexibility.

2.8.1.2 Frizelle's static & dynamic complexity

Frizelle *et al.* considers that variety and uncertainty are the two hallmarks of complexity [Fri95, Fri98, FW95, FS01]. They have used entropy to define two classes of complexity in manufacturing: structural and operational complexity. This method considers that complexity management consists of analysing the progress of parts through manufacturing operations, and of measuring the obstacles they encounter (i.e. the machines or processes that extend the lead time).

The model is based on several assumptions:

1. The system measured is stationary.
2. Each sub-system is assumed to be an immigration-emigration process.
3. The more complex a process becomes, the less reliably it will perform and the longer parts will take to be completed.
4. The most complex processes are likely to be bottlenecks.

Structural (static) complexity arises from the impact the product structure has on the resources that will produce it.

$$H_{static}(S) = -\sum_{i=1}^{M}\sum_{j=1}^{N_j} p_{ij}\log_2 p_{ij}$$

Equation 2.5 Structural (static) complexity (Frizelle's approach)

In Equation 2.5, M represents the number of resources, N_j represents the number of possible states at resource j, and p_{ij} is the probability of resource j being in state i. The outer summation represents the AND relationship between resources, and the inner summation represents the OR relationship between the states at each resource.

Operational (dynamic) complexity determines the operational behaviour from direct observations of the process, in particular on how queues behave (in terms of length, variability and composition). The main idea in the Frizelle's entropic approach is that operational complexity is reflected by queues. The investigation of the causes of queues will help detect obstacles in the process. Operational complexity (Equation 2.6) can be generated by internal sources, such as how well the facility is controlled, and by external sources (the effect of customers and markets).

$$H_{dynamic}(S) = -P\log_2 P - (1-P)P\log_2(1-P) -$$
$$-(1-P)\left(\sum_{j=1}^{M^q}\sum_{i=1}^{N_j^q} p_{ij}^q \log_2 p_{ij}^q + \sum_{j=1}^{M^m}\sum_{i=1}^{N_j^m} p_{ij}^m \log_2 p_{ij}^m + \sum_{j=1}^{M^b}\sum_{i=1}^{N_j^b} p_{ij}^b \log_2 p_{ij}^b\right)$$

Equation 2.6 Operational (dynamic) complexity (Frizelle's approach)

In Equation 2.6, P represents the probability of the system being under control, p^q is the probability of having queues of varying length greater than 1, p^m is the probability of having queues of length 1 or 0, and p^b is the probability of having non-programmable states. Similarly as for the structural complexity, M represents the number of resources, N_j represents the number of states at resource j, and $N_j = N_j^q + N_j^m + N_j^b$.

Compared to the queueing approach [Kle75, Tan95], this entropic method considers that the queue length is zero when the machine is Idle. The queue length is one when the machine is *Running* and there is no element in the queue. The system is *In Control* when there is at most one element in each queue.

2.8.1.3 Karp and Ronen's entropy-based approach to lot sizing

Karp and Ronen [KR92, KR94] have developed an entropy-based formula for the amount of information needed to determine the location of a lot along the assembly line, when its probability of being at any one station (i.e. in or before the station) is known. Given a serial production line characterized by the following parameters:

- S is the number of stations;
- P, N and B represent the number of items to be produced for a given product, the number of items per lot, and the number of lots, respectively ($P = N \cdot B$).
- C is a constant whose meaning is as following: when the entire amount is produced in a single lot, C is the ratio between the gross time (process lead time + time spent in finished goods area) and the net time (process lead time only) (i.e. $C \geq 1$),

the system's entropy as a function of the lot size, is then defined as follows:

$$H(S) = -\frac{N}{C^2 \cdot P} \cdot \log \frac{N}{P \cdot S \cdot C} - \left(\frac{1}{C} - \frac{N}{P \cdot C^2}\right) \cdot \log\left(1 - \frac{N}{P \cdot C}\right)$$

Equation 2.7 The system's entropy as a function of the lot size (Karp and Ronen)

The entropy is a function of the number of lots, number of stations and the time reference chosen (expressed by *C*). Karp and Ronen also proved that:

i) For $B \geq 2$ and $S \geq 2$, *H(S)* is decreasing;

ii) As $B \to \infty$, *H(S)* $\to 0$. This implies that there will be no information required from the line if the number of lots becomes very large (i.e. the lot size becomes very small), therefore the system will either need no control or will control itself.

The assumptions made by Karp and Ronen include:

- Deterministic identical processing times for the machines; the processing time at a given machine includes transportation and waiting time;
- A linear relationship between gross time and net time;

- Only information/data from lots located in the assembly line needs to be transmitted, i.e. since the information about the lots in the finished goods deposit is not needed to manage the line, it is considered irrelevant.

2.8.1.4 Yao's routing flexibility

Yao [Yao85] introduced the concept of entropic routing flexibility for Flexible Manufacturing Systems (FMS), which was further developed by Yao and Pei [YP90]. Their approach is based on the idea that a FMS consists of two basic modules: material and information. The parts circulation constitutes the material flow, and the data transactions form the information flow, the nature of which depends on control objectives. Starting from these modules, Yao introduces an information-theoretic concept, routing entropy, which measures the routing flexibility. He also proposes the principle of 'least reduction in entropy' for making on-line decisions on part routings in FMSs.

Consider a production task described by the following parameters:

- No_parts represents the number of part types to be produced, each of lot size $Q(t)$, $t = 1, 2, ..., No\_parts$
- Each part of type t has to go through a set of operations, which are grouped into a series of sequential subsets, $i = 1, ..., No\_Seq$. All operations in subset i have to performed before any operation in subset $(i+1)$ is initiated.
- The operations n=1, …, *No_par* in subset i have no sequence constraint and can be performed in any order.
- Each operation can be performed at one of several alternative workstations, $\mathbf{M}_n = [1, 2, ..., M_n]$

According to Yao, routing flexibility can be achieved only at the last two levels, i.e. through parallel operations and alternative workstations. Therefore, to make use of the routing flexibility of a certain part in FMS, the only required information is its parallel operations and alternative stations. In order to structure and use this information, Yao [Yao85] introduces the concept of *Next Operation List* (*NOL*). For each part entering the system, the NOL keeps track of the part's immediate next operations and the corresponding alternative stations. The list is updated every time the part finishes an operation, and thus provides a basis to characterize its routing flexibility.

The routing entropy of the production task is given by Equation 2.8:

$$H = \sum_{t=1}^{No\_parts} Q(t) \sum_{i=1}^{No\_seq(t)} \left(\sum_{n=1}^{No\_par_i(t)} H_n(t,i) + \ln No\_par_i(t)! \right),$$

Equation 2.8 The routing flexibility of the production task (Yao's approach)

$H_n(t,i)$ represents the entropy of operation n ($n = 1,\ldots,No\_par_i(t)$ in the sequential subset i for part type t and is defined as:

$$H_n(t,i) = -\sum_{\mathrm{m}_n(t,i)=1}^{M_n(t,i)} \left\{ r\left[\mathrm{m}_n(t,i)\right] / A_n(t,i) \right\} \ln \left\{ r\left[\mathrm{m}_n(t,i)\right] / A_n(t,i) \right\}$$

Equation 2.9 The operation-based routing flexibility (Yao's approach)

In Equation 2.9 $r\left[m_n(t,i)\right]$ represents the reliability of station $m_n(t,i)$, i.e. the percentage of time that the station is operational and $A_n(t,i) = \sum_{\mathrm{m}_n(i)=1}^{M_n(i)} r\left[\mathrm{m}_n(t,i)\right]$. The assumption that all stations are statistically independent in reliability is made in Equation 2.9.

The Routing principle (*The Least Reduction in Entropy principle* (LRE)) consists of the following rules:

1. If a part has several operations on its *NOL*, the operation which has the smallest H_n should be the next one performed (provided the required workstation is available). This ensures that, whenever the workstation is available, the inflexible operation is executed first, and the flexible operations are retained to cope with potential future disturbances.
2. If several parts have the same operation on their *NOL*'s, then the part which would incur the smallest ΔH_n value should be the next one processed.

In this approach, the *NOL*s play the role of interface between the material and the information modules. This model represents the first quantitative approach to the modelling of information flow in FMSs.

An assumption Yao and Pei made when comparing their method against other routing rules is that the number of parts within the system is maintained constant. Although the efficiency of Yao's method has been investigated only for single part types [YP90], the authors mentioned that a natural extension of their model would be to consider multiple part types.

2.8.1.5 Sharit's use of measures of entropy in evaluating human supervisory control

Sharit [Sha87] used entropy to evaluate human supervisory control performance in Flexible Manufacturing Systems (FMSs). FMSs were considered particularly appealing for this work due to their combinatorial complexity, which in turn determines a reduction in the level of predictability of the system status as a function of the system's events. The objective of Sharit's work was to identify the trade–offs between the capabilities and limitations of the human supervisory control, with the aim of learning from the insights obtained. The entropy concept was used as an explanatory means for the most important findings of the study.

Various classes of information on the system status were provided in different forms, and process and informational variability and uncertainty were introduced in the experiments. Variability of the objective was also introduced through the number of performance measures that had to be optimised simultaneously, such as machine utilisation, product quality, and number of operations completed prior to the deadline [Sha87].

Three levels of control were defined depending on the scope of control, higher levels of control corresponding to changing more elements of the system simultaneously through each action. Due to the nature of FMSs, this represents a more risky strategy. The input–output structure representing the transitions from information to control was quantified through the use of entropy.

Sharit based his work on the method used by Kvålseth *et al.* [KCK76], who proposed the *sampling entropy index* (SEI) as a single measure of the degree of structure in a sampling pattern. Sharit adapted the formula used by Kvålseth *et al.*, and defined SEI as below:

$$\widehat{H} = -\sum_i \sum_j (u_i \hat{p}_{ij}) \log_2 (u_i \hat{p}_{ij})$$

Equation 2.10 The estimated entropy of the sampling transition structure in Sharit's approach

$$SEI = \hat{H} / H_{\max}$$

Equation 2.11 The sampling entropy index in Sharit's approach

In Equation 2.10 u_i and $\hat{p}_{ij}$ represent the relative frequency of utilization of information of type i, and the estimated probability of selecting the j^{th} control action following the acquisition of the i^{th}

type information, respectively. $\hat{H}$ is the estimated entropy of the sampling transition structure, which reaches the maximum value $H_{\max}$ when all transitions are equiprobable.

2.8.2 Practical issues

In this section, we review the practical issues related to each of the selected measures of manufacturing complexity.

2.8.2.1 Deshmukh's static complexity

Deshmukh *et al.* discussed the properties of their static complexity measure. These properties represent useful and predictive guidelines for system designers and include:

- Static complexity of processing a part mix is minimum when the similarity between the processing requirements is minimum, and is maximum when the similarity between the processing requirements is maximum.
- Increasing the number of parts, or number of operations, or number of machines, has a higher effect on the system complexity when the system has a smaller size, than when the system is large.
- The variation in operational requirements will have maximum effect when the system has less static complexity, as compared to when the system is operating at maximum complexity.

Deshmukh, Talavage and Barash also defined several relationships between static complexity and classical performance measures such as the average waiting time for a part mix under a given control policy [Des93, DTB98]. On the issue of the optimal level of static complexity to be embedded in a system, the authors mentioned the trade-off that exists between increasing decision making or resources costs, and improved system performance.

2.8.2.2 Frizelle's static & dynamic complexity

According to Frizelle [Fri95, Fri98, FW95], static complexity gives a measure of the intrinsic difficulty for the process of producing the required number and type of products in the required period of time. It needs to be measured over a significantly long period of time (usually a year). As concerns the operational phase, the states are classified as *programmable* or *non-programmable*, according to whether they are planned or not. The operational states for a generic system include: *programmable* states (Run, Set-up and Idle), and *non-programmable* states (Reject, Rework, Absenteeism and Resource Breakdown). This approach is based on the understanding that non-programmable states reduce the time available for processing useful work, possibly creating bottlenecks.

This method requires real-time process observations to be taken in a representative period (in order for the stationarity assumption to be satisfied) and at regular intervals, ideally including all the products produced in the analysed facility. The timing, frequency and duration of measurements must therefore be decided using detailed information on the process (such as machine cycle time, product lead time, shift information, or frequency of breakdowns).

Structural complexity can be reduced by simplifying products and processes, and it can also be planned. Operational complexity must be controlled to improve schedule adherence and process stability, but, as obstacles occur at random, it cannot be planned. The results obtained by applying this technique should reveal or confirm existing problems.

2.8.2.3 Karp's entropy-based approach to lot sizing

The method Karp & Ronen developed is dedicated to flow line systems and was aimed to prove that, for a single type of product, smaller lots imply less information requirements. Karp & Ronen [KR92] highlighted, however, that these benefits can only be achieved in conjunction with efficient and high quality management methods such as Total Quality Management (TQM), Total

Quality Control (TQC) or Just-in-Time (JIT). This model also shows the relationships between improvement activities, such as set-up and lead time reduction, and information needs.

The main message is therefore that for the same product, smaller lot sizes are more cost–effective in terms of information needs for on–line control. This is explained by the fact that for bigger lot sizes the uncertainty in the system is higher, and therefore the level of information (entropy) required to understand and control it is higher. Furthermore, for a given lot size, the entropy increases with the increase in the line length, S (Equation 2.7).

For different values of the time reference, C, the entropy required for controlling the system for a given configuration (lot size and number of machines) is different. Higher values of C will yield lower values of the entropy. This indicates that, according to Karp and Ronen, if the amount of gross time in the system is significantly higher than the process lead time, then the level of control to be exercised on the lot (via the amount of information gathered) is lower. In this case there would be no benefit in sampling the system status more often, but the costs incurred by doing this would increase.

These insights are applicable to JIT systems, characterized by low set-up and transportation time and no process variability. For these systems small lot sizes yield higher throughput, lower lead times, less operating expenses, better due date performance and less work in process. This method only evaluates the on–line control information. This implies that the scheduling and planning information involved is not assessed by the method.

2.8.2.4 Yao's routing flexibility

The objective of Yao's method is to control and utilize the flexibility pertaining to part routing in flexible manufacturing systems. The practical reasoning behind this approach is that whenever a machine is available, the inflexible operation should be processed first, and the flexible operations retained to cope with potential future disturbances [Yao85].

Yao and Pei [YP90] compared the results obtained by applying the *Least Reduction in Entropy* principle (Section 2.8.1.4) with those obtained by using the Shortest Processing Time (SPT) rule. They found that LRE either outperforms, or is as good as SPT in terms of makespan and machine utilization.

Yao [Yao85] mentioned that he has not investigated the cost-effectiveness of this approach.

> *"There is also a cost-benefit problem: what is the cost of collecting and retrieving the required information and what is the net profit (in terms of improving system performance) obtained through the information processing? Although we are quite sure that in our approach the amount of information carried on the NOLs is the minimum required for the purpose of controlling and utilizing flexibility, we are not able at this point to quantify the net gain in system performance through this approach".*

2.8.2.5 Sharit's use of measures of entropy in evaluating human supervisory control

In Sharit's approach [Sha87], increasing values of the Sampling Entropy Index indicate reduced degrees of structuring of the sampling pattern. H is interpreted as the average uncertainty associated with the transitions between the human's acquisition of information and the execution of control actions. From an information-theoretic point of view, high values of SEI indicate a more flexible control strategy (or a less structured transitional environment [AMO93]), in terms of the control action executed, given that a certain type of information has been gathered [Sha87].

The analytical results showed significant but negative correlation levels between the measured levels of the system performance and SEI. This means that the task performance improved as the transition from acquisition of graphic information to control actions became more structured. Sharit provides two possible explanations for the poorer performance:

- The human believed that there was more information or diagnostic value associated with the displays than there actually was, and acted accordingly;
- The execution of control actions across several control levels increased the potential for the potentially adverse effects of combinatorial complexity to become manifest.

More generally, this implies *a lesser understanding between information and control*, and therefore a reduced capability of predicting and controlling the system behaviour. However, the results obtained show that although combinatorial complexity adversely affects both the human and the computer, the human has the greater potential for coping with this factor. The author also emphasises the importance of training in the development of effective strategies for the control actions susceptible to combinatorial complexity.

2.9 Conclusions and Summary

This chapter has briefly reviewed the main concepts in the definition, classification, control and measurement of manufacturing systems, with a focus on sources of complexity and existing information-theoretic methods for modelling and measuring complexity. The conclusions of the literature review are presented next.

Manufacturing entails a significant number of characteristics that need to be managed, in the design and operational phases. These features include the size and layout of the system, the type and dynamics of industry, the customer contracts and relationships, and the uncertainty (Sections 2.1 to 2.5). On the other hand, the existing methods for planning and control assume perfect information, and low uncertainty and variability as prerequisites (Section 2.4). Furthermore, the modern manufacturing partnership and e-manufacturing eras (Section 2.2) place an ever increased emphasis on the criticality of high quality (i.e. accurate, timely, comprehensive, relevant, and in the right format) information. Therefore, information is at least as critical as material in modern manufacturing. Competitiveness is based not only on reliability, speed and cost. Differentiation will be achieved through information management and processing.

However, as many of the existing performance measures are localised and average-based (Section 2.5), they are not capable to capture and assess systemic cause-effect relationships and provide appropriate solutions. The global measures of costs and value have the limitation of often not allowing a hierarchical analysis of their constituents. In these conditions, a shift from reductionist to analytical thinking approaches in system design and management is required in order to achieve a better system understanding, management and control (Section 2.6).

As entropy represents the amount of information required to define the state of the system (Section 2.7), it represents a valid and powerful solution for integrating various systemic aspects of manufacturing complexity. The advantages of using an entropic measure of manufacturing complexity include:

- The ability to identify and assess cause effect relationships;
- The ability to integrate systemic characteristics in a single measure;
- Transferability;
- Visibility through analysis of its components;
- Adaptability and flexibility;
- Comparability.

The above properties match the requirements of a manufacturing measurement and control method as identified in Section 1.1.

Advanced entropic-based methods for measuring structural and operational aspects of complexity have been provided by Deshmukh, Frizelle and Efstathiou *et al.* (Sections 2.7 and 2.8). Yao's work [Yao85, YP90] showed that complexity and flexibility are closely linked. The limitations of the existing information-theoretic methods include:

1. Localised definitions of the aspects of complexity into structural and operational (Efstathiou *et al.*, Frizelle, and Karp and Ronen), static (Deshmukh), routing (Yao), control (Sharit) without providing a systemic definition of manufacturing complexity and of the relationships between various complexity classes.
2. Focus on queues and material flow issues only (Frizelle).
3. Not taking into account (Frizelle, Karp and Ronen), or incompletely taking into account the complexity of scheduling (Deshmukh and Yao).
4. Lack of, or insufficiently detailed practical methodology for applying the measure into real case studies. Issues to be addressed include the impact of imperfect information, cost of the measurements, or conversion of the results into meaningful information and recommendations for generic and specific issues on manufacturing system design and management.
5. The need for further investigation of the predictive capabilities of the entropic measures.

This chapter has confirmed the novelty of the research motivation presented in Section 1.1, the need for addressing the research questions presented in Section 1.2, and the fact that entropy represents a valid approach to modelling and measuring manufacturing complexity.

3 An investigation of process variability's effects on a kanban system

If you want to succeed, limit yourself.

Charles Augustin Sainte-Beuve[Sai]

This chapter uses simulation to investigate the qualitative and quantitative aspects of complexity and the related cause-effect relationships between material and information flows in a simple and predictable manufacturing environment, i.e. a flow-line kanban system, characterized by processing variability. Simulation allowed the assessment of the impact of various system configurations and process variability on the system performance. The analysis of the results provided insights into optimal system design in order to cope with process variability. Therefore, the chapter addresses the research questions 1 and 4 to 7 (Section 1.2) for a simple manufacturing system. The insights obtained in this chapter have been used in the development of the theoretical framework presented in Chapter 4.

The research questions in Section 1.2 adapted for the kanban system become:

- How do the aspects of complexity, i.e. *structural variability* (i.e. varying the number of kanbans and the lot size) and *operational variability* (i.e. processing time) affect the system performance, in terms of throughput, average machine utilisation, average lead time and average work-in-progress (question 1 and 4);
- What relationships exist between processing time variability and system capacity (questions 5, 6 and 7);
- What methods of controlling the system performance can be designed on the basis of the insights obtained from the previous analyses, and what are their relative merits (questions 4, 5, 6 and 7).

In order to answer these questions we simulated the flow-line kanban systems. The simulations have considered a large number of system configurations, obtained by varying both the number of kanbans between successive machines and the capacity of containers. The machine processing times have been generated employing the truncated normal and gamma distributions, a large range of variability levels being taken into account. For each system configuration, and each distribution and variability level used to obtain the machine processing times, several performance measures have been monitored throughout the simulation. They include the throughput of the system, the average machine utilisation, the average work-in-progress, and the average lead time. These performance metrics are analysed individually as well as in relationship with each other, from both a qualitative and quantitative standpoint. Based on the insights gained from these analyses, the chapter discusses possible methods of system control (e.g. varying the number of kanbans and/or the container capacity, and controlling the processing time variability), and assesses their effectiveness for flow-line kanban systems.

As kanban systems are an important component of JIT systems, the results presented in this chapter first document why and assess how process time variability acts to limit JIT effectiveness by restricting the utility of kanbans. Second, these results show why standardized operations are required as a planning prerequisite to allow kanban execution to succeed. Last but not least, this chapter presents and discusses the complexity-related issues that need to be taken into account in order to achieve a better understanding and control of a kanban system characterized by process variability. It therefore represents the opening act to the work on manufacturing complexity presented in this thesis.

The contribution of this work resides firstly in the large number of variability classes considered for investigation. Secondly, this is further accompanied by an integrative discussion and interpretation of the results, focussed on the trade-offs among the various performance measures monitored, and on possible methods of system optimization.

Two possible methods of controlling the system performance, i.e. varying the number of kanbans and/or the lot size, and controlling the processing time variability have emerged from the analysis of the simulation results. These methods could be applied either individually or jointly, in order to improve the system performance. An assessment of their effectiveness is performed on the basis of the simulation results.

The remainder of the chapter is organized as follows. In Section 3.1 we briefly review previous work on variability in kanban and JIT production systems. Section 3.2 describes our approach, in terms of both model and method used. Next, the results of the simulation are presented and discussed individually in Section 3.3. A discussion of the effects of the initial modelling assumptions on the simulation results is carried out in Section 3.4. An overall analysis of the results is then performed in Section 3.5. This includes the investigation of the trade-offs between the individual measures presented in Section 3.3, a discussion of two methods of system optimization, as well as a link with the next chapter on manufacturing complexity. The chapter concludes with a summary.

3.1 Investigating the effects of variability in kanban and JIT systems – a literature review

Variability is a reality and a key feature in manufacturing. The quality of raw material, the number and type of products required, the number of resources available and the processing times are but a few examples of elements that could vary in a manufacturing system. Due to the complex relationships that exist in a manufacturing system, variability needs to be under regular monitoring and control, as it directly influences the system performance [CR96, ESC98, Har95, Hen90, KA97, Sav96]. Indeed, variability affects the throughput and lead times, the work-in-progress (WIP) inventories, the material requirements, and should be fedback into the schedules. This ultimately has an impact on an organisation's ability to cost-effectively satisfy its customers.

The on-line control mechanism of any manufacturing system requires gathering data on the system status, making decisions on the basis of these data, and disseminating these decisions in the system. In this way, the material flow is controlled via the information flow. On the other hand, due to the control mechanism specific to kanban-based systems, information is transmitted throughout the system, via kanbans, at the same time as the material [Mon93, Sch82]. Due to these processes, material flow variability inherently generates information flow variability. Nevertheless, this aspect of variability has been neglected so far.

This section presents a brief review of the main issues investigated by previous work on variability and control-related topics in kanban and JIT systems, in terms of the methods used, the topics investigated and the specific results obtained.

The methods used in investigating kanban and JIT systems include *surveys and literature review* [CS92, GS91], *analytical models* [DHMG89, KA97, NS96, PC97, SB98], *conceptual models* [Fun95, Ram93], *simulation* [HRT83, MSW92, Sar89, Sav96], *simulation and analytical approach* [And97, SB92], and *case-studies* [FF92, Fun89].

Some of the performance measures used for assessing kanban and JIT systems include: *capacity utilisation* [MSW92, Sav96], *overtime* [HRT83], *throughput* [And97, SA96], *system time* [And97, DHMG89], *cost* [HRT83], and *total WIP* [DHMG89, Sav96, SB92]. Many studies (e.g. [And97, HRT83, MSW92]) assume a perfect production process: no scrap, no rework and no machine breakdowns. Also, no transportation time is usually considered [And97, HRT83, MSW92, Sav96].

The most relevant issues investigated include:

- *The sensitivity of the simulation results to the different distributions used to describe processing times*. Many studies (e.g. [And97, HRT83, Sav96]) do not justify the choice of distribution and the effect that a different distribution would have on the results. The approach of Muralidhar *et al.* [MSW92] is an exception from this point of view, as it investigates the effect of the distribution followed by the processing time on system performance. This approach employs log-normal, truncated normal and gamma distributions and uses average capacity utilisation as the only measure of system performance. Muralidhar *et al.* [MSW92] concluded that no significant difference in performance could be attributed to the choice of distribution, and that the performance of a given system is a function of the coefficient of variation. They recommended gamma distribution as the most appropriate for modelling processing times in JIT systems, as it specifically meets the processing time requirements and is computationally efficient.

- *The effect of processing time variability on system performance*. An increase in the variability of processing times leads to a decrease in production rate [HRT83, MSW92, Sav96] and average capacity utilisation [MSW92, Sav96]. Chu and Shih [CS92] identify this problem as the trade-off between increasing the inventory levels and using overtime.
- *The identification of the optimal number of kanbans and container size.* Andijani [And97], Panayiotou and Cassandras [PC97], Ramesh *et al.* [RPT97a, RPT97b], and Sarker and Balan [SB98] developed analytical methods to address the trade-off between maximizing throughput rate and minimizing system time (or WIP) in JIT production systems.
- *The dependence of the WIP on the workstations and material handling system*. By using both simulation and analytical results from queueing theory, Srinivasan and Bozer [SB92] showed that the WIP associated with the workstations usually far exceeds the WIP associated with the material handling system. Reducing the variance of the processing times has a greater impact on overall WIP than reducing the variance of the handling times [SB92].

To summarize, analytical methods have been used so far to investigate the effects of variability on simple or dedicated manufacturing kanban and JIT systems, as well as to decide the optimal system configuration for deterministic behaviour. For more complex systems and behavioural patterns, simulation proved the only viable solution from the point of view of both quantitative and qualitative analysis. However, there is a high dependence of the simulation results on the specific system investigated. Therefore, the generalization capabilities of the results obtained by simulation are often limited to the qualitative level.

3.2 Description of the approach and implementation details

3.2.1 Approach and model description

The research methodology consists of (i) designing a computer-based dynamically configurable model of a flow-line kanban system, and (ii) simulating the system for different structural and operational parameters. The structural variability is modelled by varying the system configuration in terms of:

- the number of kanbans (the number of in-process containers);
- the lot size (the container capacity).

For a given system configuration, the operational variability is then modelled by considering two different distributions, and 11 coefficients of variation for the machine processing times.

Our study considers a generic flow-line kanban system with the following characteristics:

1. The single-card kanban control and variable withdrawal cycle–fixed order quantity policy are used [Mon93, Sav96, Sch82, SCH+95].
2. There is a single machine in each workstation.
3. Jobs visit each machine in the production line.
4. The first machine never waits for material (unlimited availability of raw materials).
5. The last machine never waits for demand. Hence, each machine in the line will start processing a part whenever the following two conditions are fulfilled: (i) there is at least one element in its input buffer and (ii) there is at least one non-full container in its output buffer.
6. There is a single class of products, i.e. no set-up times are included in the model.
7. Mean processing time at each stage is one time unit.

8. Material handling and transportation times are considered negligible.
9. All the machines have the same mean processing times and distributions.
10. No breakdowns are implemented.

Under these assumptions, no machine will start work unless there is an available unit in the container for the part to be processed. Therefore, machines never block, but they may be idle due either to lack of material, or to lack of demand (and container). The performance measures recorded throughout the simulation are:

1. Throughput, defined as the number of parts produced by the system during the simulated time;
2. Capacity utilisation for each machine in the system;
3. Average capacity utilisation;
4. Average WIP per buffer;
5. Average WIP in the system (buffers plus machines);
6. Average lead time.

The structure of the modelled system is depicted in Figure 3.1, where:

- Input_Buffer represents the input buffer, considered infinite;
- $L \geq 1$ is the number of machines in the system;
- M_1, M_2, …, M_L represent the L identical machines;
- The $L-1$ buffers have the same capacity, namely $No\_kanbans \times Lot\_size$, with $No\_kanbans \geq 1$ and $Lot\_size \geq 1$ denoting the number of kanbans between successive machines and the batch size (container capacity), respectively. No other dedicated storage buffers are included in the model.

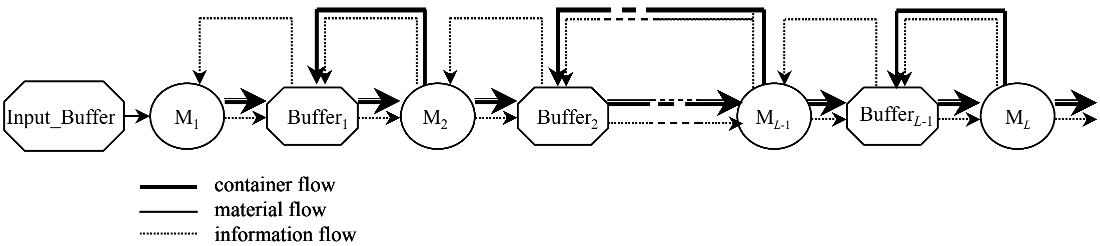

Figure 3.1 The modelled flow-line kanban system

3.2.2 Implementation details and discussion

A dynamically configurable model of the system described in Section 3.2.1 was constructed using the simulation package Witness [Lan98]. Witness is a manufacturing simulation software marketed by Lanner Group. This software is characterized by a high level of modelling flexibility due to its ability to program the input and output rules and actions associated with any entity in the simulation model, such as resources, labour and buffers, and to model manufacturing activities and throughputs [Lan98, LK91].

A system configuration is determined by the combination (number of kanbans between successive machines; container capacity). For each system configuration, and each distribution and variability level used to obtain the machine processing times, four simulations – each using a different set of independent random number streams – were run, and data on the system behaviour were recorded. The simulations were run for 10000 time units, preceded by a 1000 time units warm-up period. The graphs presented in the next section were obtained by averaging the data obtained over the four different sets of random number streams. This increases the validity and generality of the results. The choice of the number of different random streams was determined by the total simulation time required to run all the configurations (the model execution cost).

The parameters of the simulation took the following values:

- Number of machines: L=10;
- *No_kanbans*: 1 to 5;

- *Lot_size*: 1 to 5;
- Mean processing time: μ=1.
- Coefficient of variation: $CV \in \{0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1\}$.
- The processing times were varied according to the following distributions [LK91, MSW92]:
  1. Gamma distribution (GAD) with mean μ and coefficient of variation *CV*.
  2. Truncated normal distribution (TND), with mean μ, coefficient of variation *CV*, and the lower and upper truncation points described below.

The lower and upper truncation points chosen for the TND are 0 and 10, respectively. Choosing the minimum truncation point at 0 overcomes the problem of negative values of the random variable provided by the normal distribution. As concerns the upper truncation point, we used the formulae in Muralidhar *et al.* [MSW92] and Kreyszig [Kre93] to calculate the probabilities that the random variables generated by the normal distribution are higher than 10. As these probabilities are null for all the coefficients of variation investigated, we conclude that the simulation results obtained for GAD and TND for similar system configurations are comparable.

For each of the two processing time distribution types, a number of 1100 simulations were required for the set of system configurations taken into account. The average time required per simulation for processing times following GAD on a 200Mhz Pentium PC was 2.13 minutes. This translates in over 39 hours for the 1100 simulations. The duration of a simulation is further increased for processing times following the TND, due to the intricate computations associated with it [MSW92].

3.3 Presentation and discussion of the simulation results

The simulation results in terms of throughput, average capacity utilisation, average WIP and average lead time for the simulated system are presented and discussed in this section.

3.3.1 The Throughput

This section analyses the complex relationships between the system throughput and various systemic structural and operational parameters, from both a quantitative and a qualitative standpoint. The parameters taken into account include the number of kanbans, the lot sizes, and the processing time distribution type and coefficient of variation. A global view of the system throughput for processing times following GAD for different coefficients of variation, numbers of kanbans and lot sizes is presented in Figure 3.2.

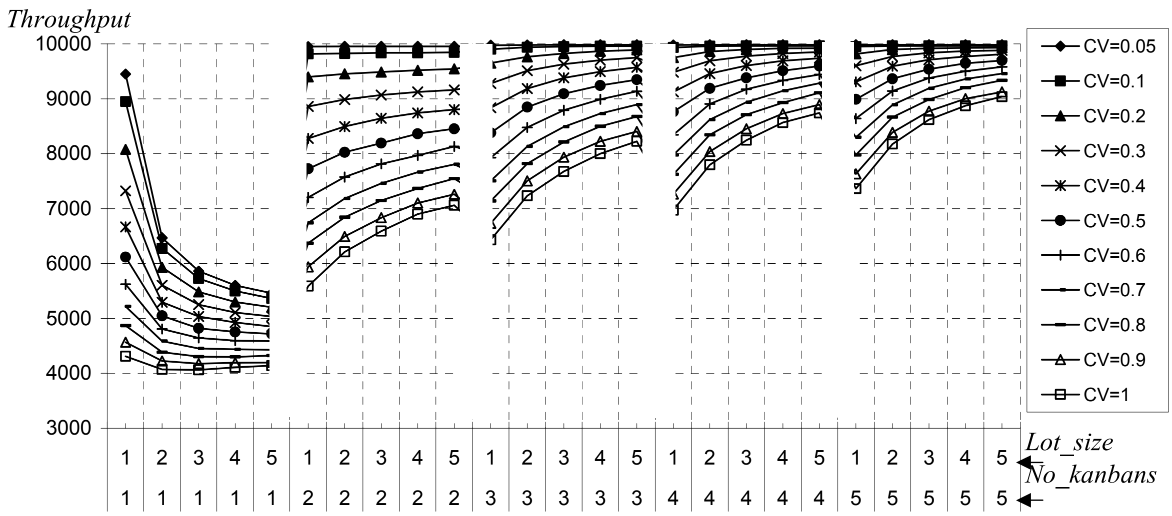

Figure 3.2 The Throughput for GAD, $1 \le No\_kanbans \le 5$, $1 \le Lot\_size \le 5$, and different coefficients of variation

A selective presentation of the differences between the throughput values obtained for GAD and TND for similar coefficients of variation and several (*No_kanbans, Lot_size*) combinations is presented in Table 3.1. These differences are smaller than 4% for all the configurations investigated. This indicates that *for a given configuration of a flow-line kanban system, throughput does not significantly depend on the distribution type, but on the coefficient of variation*. Therefore, although all the results presented next have been obtained for processing times following the Gamma distribution, they represent a global picture of the throughput behaviour for processing times following any distribution.

Table 3.1 A quantitative assessment of the percentage differences between the Throughput for TND and GAD, $No\_kanbans \in \{2,5\}$ and $1 \le Lot\_size \le 5$, calculated as: $\left|100\times\left(Throughput\left(\text{GAD}\right)-Throughput\left(\text{TND}\right)\right)\right|/Throughput(\text{GAD})$

$No\_kanbans$	Lot_size	$CV=0.1$	$CV=0.3$	$CV=0.5$	$CV=0.7$	$CV=0.9$
2	1	0.23	0.66	1.35	1.40	3.49
2	2	0.13	0.83	1.91	1.93	2.68
2	3	0.08	0.41	1.16	1.83	2.80
2	4	0.05	0.32	0.84	1.52	2.00
2	5	0.06	0.26	0.86	1.56	1.76
5	1	0.15	0.38	1.10	1.31	2.11
5	2	0.13	0.97	1.66	1.79	1.97
5	3	0.07	0.29	0.91	1.48	1.68
5	4	0.07	0.20	0.58	1.31	1.85
5	5	0.07	0.17	0.33	1.26	1.32

For clarity, the various aspects depicted in Figure 3.2 will be presented in simplified graphs and discussed next.

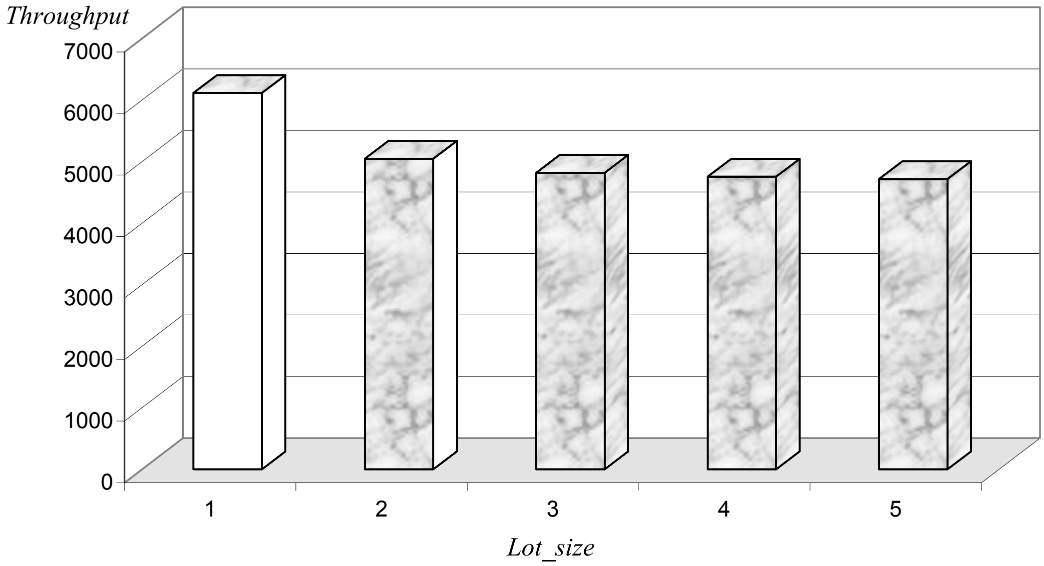

Figure 3.3 The Throughput for a single kanban configuration, $1 \le Lot\_size \le 5$ **and** $CV = 0.5$

For the one-kanban configuration, an increase in the lot size determines a Throughput reduction (Figure 3.3). A single kanban with a one-unit container does not ensure the highest throughput, because the stations will be allowed to spend a significant amount of time in the Idle state due to the simultaneous lack of demand (ensured by kanbans) and containers. Nevertheless, this configuration ensures the smoothest flow of material and information through the system and is the ideal configuration for JIT systems, in which the products are produced as soon as needed, and only then [Mon93, Sch82]. The requirement of zero inventories as defined by the JIT philosophy is thus accomplished in this configuration.

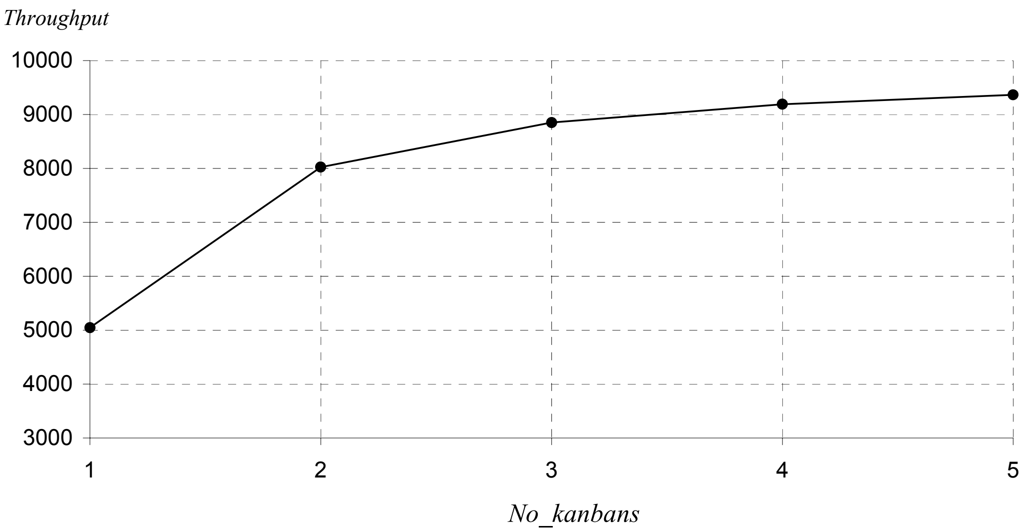

Figure 3.4 The effect of increasing the number of kanbans on the Throughput, for $Lot\_size = 2$ **and** $CV = 0.5$

Furthermore, the graph in Figure 3.4 shows that *a significant increase in throughput is obtained when switching from 1 to 2 kanbans*. A similar increase is not achieved when passing from 2 to 3, 3 to 4, and 4 to 5 kanbans, respectively. This reflects the significant gain in throughput obtained by investing in a minimum number of containers, which are moved from one station to another in a negligible period of time. The structural configuration to be chosen depends on the relationship between demand rate, number of resources available, processing time and the level of variability embedded in the system. The single-container configuration (equivalent, in our approach, to the one-kanban case) is the ideal approach in a JIT-comprehensive system, characterized by no variability. Due to this reason, it will not be discussed in detail in this chapter.

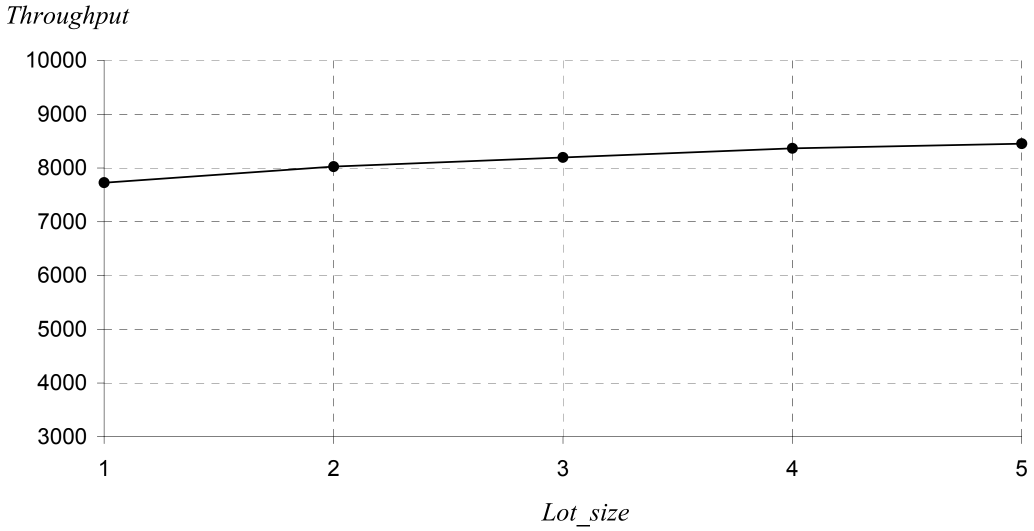

Figure 3.5 The effect of increasing the lot size on Throughput, for $No\_kanbans = 2$ **and** $CV = 0.5$

For negligible transportation times and *No_kanbans* > 1, *the Throughput will increase with an increase in either lot size or number of kanbans* (Figure 3.4 and Figure 3.5).

Figure 3.6 indicates that *the higher the coefficient of variation, the lower the throughput*. Furthermore, if the extent of variability is not known precisely, the effective system capacity will be inaccurately assessed. This further leads to the inability to accurately predict the system behaviour. If this situation occurs, the graphs in Figure 3.6 can be used to quantify the difference between the expected and the achieved throughput, and thus to detect the real level of variability. This information can then be used to control the system.

Higher buffer sizes render higher throughput values (Figure 3.6), as they reduce the effect of variability along the line. *The throughput lost due to variation is thus recovered through a higher number of kanbans and/or higher lot sizes*. This effect is especially visible for *CV*s higher than 0.5.

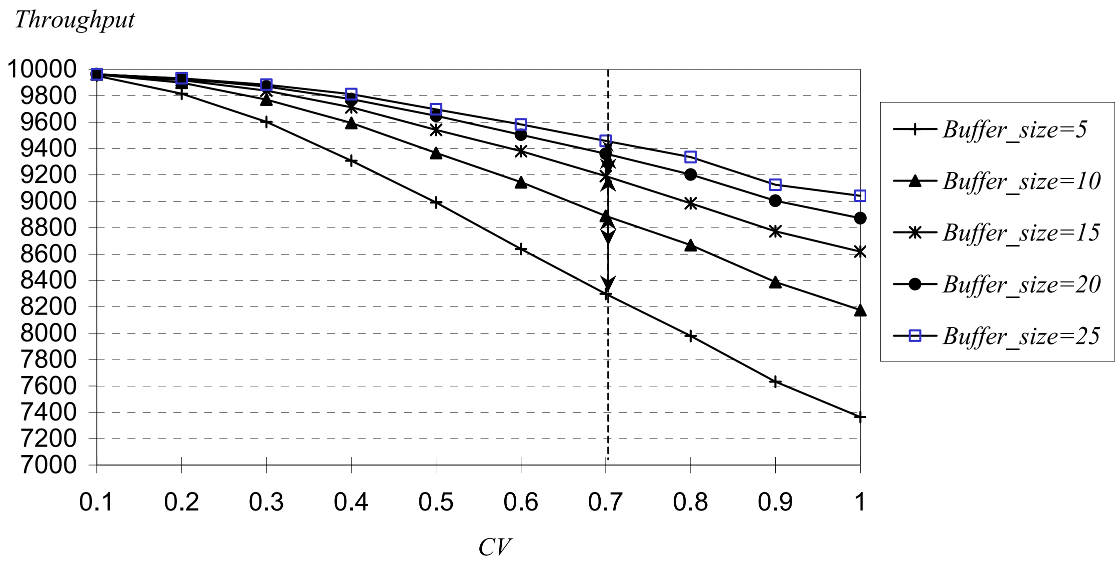

Figure 3.6 Throughput vs. Coefficient of Variation for different buffer sizes and $Lot\_size \leq No\_kanbans$

The quantitative analysis of the increase in throughput determined by an increase in buffer size is facilitated by the graphs in Figure 3.6. For example, for *CV*=0.7, approximate increases of 600, 300, 200 and 100 units in throughput have been obtained by increasing the buffer size from 5 to 10, 10 to 15, 15 to 20 and 20 to 25, respectively. Therefore, *the relationship between a given increase in buffer size and the obtained increase in throughput is not linear*.

Furthermore, the results in Figure 3.7 show that *for the same buffer size, a higher throughput is obtained for smaller lot sizes*. Smaller lot sizes ensure that the WIP is moved more frequently from one machine to another, which not only reduces the idle periods of the machines, but also the WIP levels in the system.

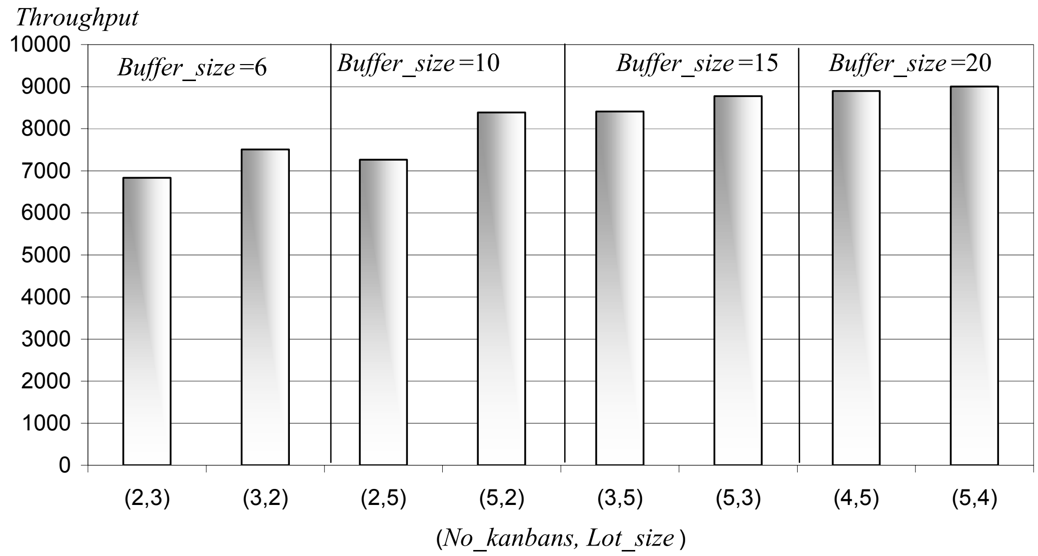

Figure 3.7 Throughput dependence on the (*No_kanbans, Lot_size*) combination for $CV = 0.9$

3.3.2 Average Capacity Utilisation

Because the system was simulated for 10000 time units, with unit-mean machine cycle time, the maximum system throughput (which corresponds to constant machine cycle time) is 10000. Therefore, the quantity $Throughput/100$ is comparable, in terms of range of values, with the average capacity utilisation.

For our homogeneous system, the average machine utilisation is identical with the curve $Throughput/100$, and therefore does not depend on the distribution type, but on the value of the Coefficient of Variation. As a result, the average capacity utilisation presents the same behavioural pattern as the throughput.

3.3.3 Work-in-Progress (WIP)

This section investigates how processing times variability affects the WIP in the system. The average WIP per buffer, the WIP distribution throughout the line, and the average WIP in the system are presented and discussed. The effects of varying the number of kanbans and the lot size, as well as of variable processing times on these measures are examined.

3.3.3.1 Average WIP per buffer

The average WIP per buffer, denoted $\overline{WIP_{\text{buf}}}$, is calculated by dividing the sum of the average WIP in each buffer throughout the simulation by the total number of buffers.

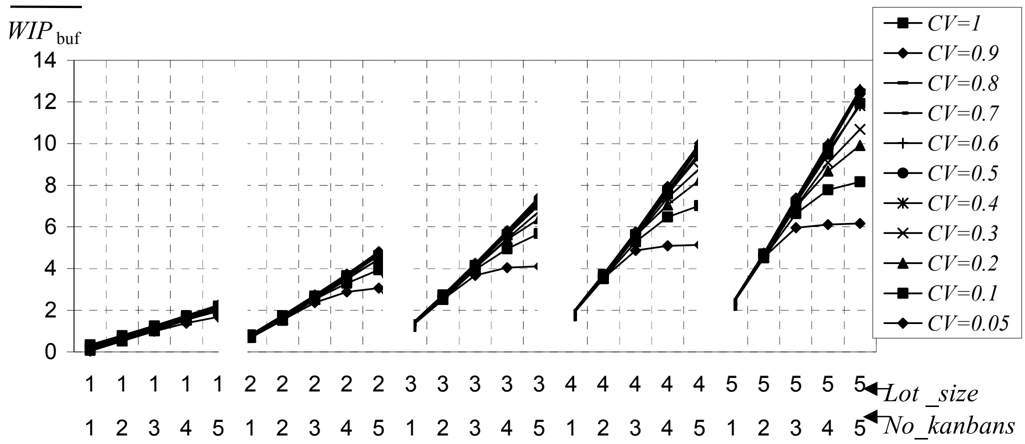

Figure 3.8 Average *WIP* per buffer for GAD with different Coefficients of Variation

For a given lot size, the average WIP per buffer has three behavioural stages (Figure 3.8 and Figure 3.9). In the first stage, up to the points A1 (for *CV*=0.5) and B1 (for *CV*=0.9) in Figure 3.9, *the average WIP per buffer increases linearly with an increase in the number of kanbans.*

The data in Figure 3.8 and Figure 3.9 show that the gradient of the line followed by the average WIP per buffer for this first behavioural stage is close to 0.5, and thus independent of CV. On the other hand, the length of this stage depends on CV.

In the second stage (segments A1-A2 and B1-B2 in Figure 3.9), $\overline{WIP_{\text{buf}}}$ follows a line of lower gradient than that of the first line. *In the last stage* (from A2 and B2 onwards) *a stable value is* *reached*. In Figure 3.8, this stabilisation can only be seen for low values of *CV*. For a given buffer size, *the saturation value of the average WIP per buffer depends on CV and on the Lot_size/No_kanbans ratio*. *The smaller the CV is, the faster the saturation value is reached.*

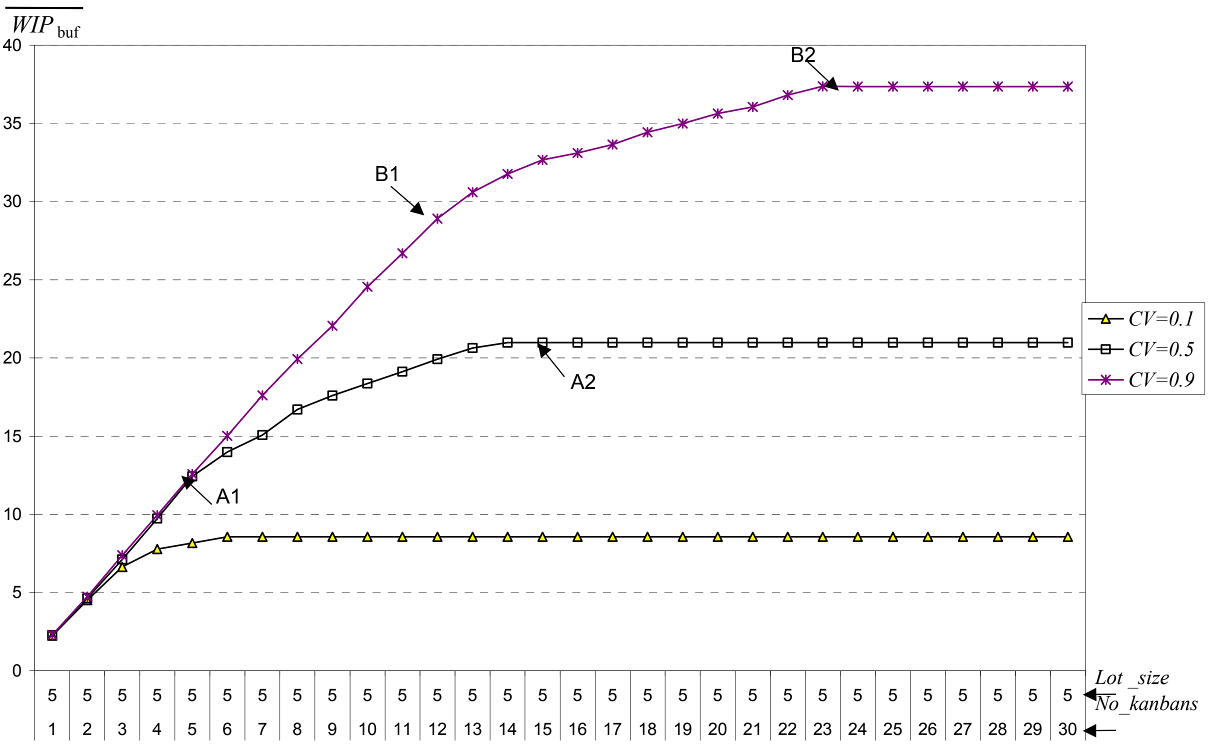

Figure 3.9 The stabilisation of $\overline{WIP}_{\text{buf}}$ for buffer sizes between 5 and 150 and $Lot\_size = 5$, for GAD and a fixed set of random number streams

To summarize, in the first stage, the average WIP per buffer is half of the buffer capacity. This "rate of return" decreases when the buffer capacity is increased above a critical level (stages two and three). Hence, when a buffer is fully utilized the average WIP per buffer is 50% of the buffer capacity. This means that the cost of introducing buffers above a critical level (A1 and B1 in Figure 3.9)—in terms of WIP costs and increased lead time—increases at a higher rate than the recovered capacity.

The differences between the values taken by $\overline{WIP_{\text{buf}}}$ for TND ($\overline{WIP_{\text{buf}}^{\text{TND}}}$) and GAD ($\overline{WIP_{\text{buf}}^{\text{GAD}}}$) are presented in Table 3.2. The largest differences are obtained for high values of *CV* (≥ 0.7), and *No_kanbans* and *Lot_size* bigger than 4. However, more relevant is the fact that the average WIP per buffer follows the same "shape" for both distributions. Therefore, *while the values taken by* $\overline{WIP_{\text{buf}}}$ *depend on the distribution type more significantly than the throughput values* (especially for high coefficients of variation), *the qualitative behaviour of the average WIP per buffer is independent on the distribution type.*

Table 3.2 A quantitative assessment of the percentage differences between average WIP per buffer for TND and GAD, $No\_kanbans \in \{2,5\}$ and $1 \leq Lot\_size \leq 5$, calculated as: $\left|100\times\left(\overline{WIP_{\text{buf}}^{\text{TND}}} - \overline{WIP_{\text{buf}}^{\text{GAD}}}\right)\right| \Big/ \overline{WIP_{\text{buf}}^{\text{GAD}}}$

$No\_kanbans$	Lot_size	$CV = 0.1$	$CV = 0.3$	$CV = 0.5$	$CV = 0.7$	$CV = 0.9$
2	1	0.00	0.00	0.00	0.00	1.23
2	2	0.66	0.63	0.00	0.59	2.86
2	3	3.95	0.40	1.53	2.61	3.30
2	4	3.33	0.29	1.39	3.52	3.48
2	5	8.38	1.57	2.36	2.55	5.19
5	1	0.45	0.44	0.44	0.43	0.00
5	2	0.44	0.44	0.86	0.86	1.69
5	3	3.46	1.29	0.56	1.67	4.47
5	4	0.64	0.55	1.85	4.07	7.44
5	5	3.55	8.80	1.53	8.27	10.66

Figure 3.10 depicts the percentage differences between $\overline{WIP_{\text{buf}}}$ for several pairs of system configurations. The configurations in each such pair have the same buffer size, but differ in their (*No_kanbans*, *Lot_size*) parameter combination. The results in Figure 3.10 indicate that for low CVs the average WIP per buffer highly depends on the (*No_kanbans*, *Lot_size*) combination, rather than on the buffer size alone. This difference decreases with an increase in the coefficient

of variation. For example, for a buffer size of 15 and CV=0.05, the difference between the configurations (3, 5) and (5, 3) is about 45%. For the same buffer size and CV=1, this difference is less than 5%.

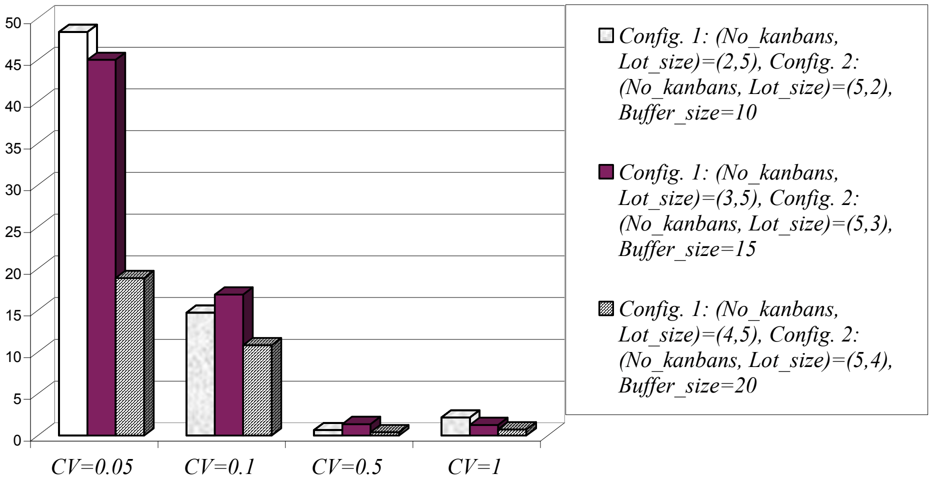

Figure 3.10 The percentage differences between $\overline{WIP_{\mathrm{buf}}}$ for a set of configuration pairs, calculated as $\left|100\times\left(\overline{WIP^{1}_{\mathrm{buf}}}-\overline{WIP^{2}_{\mathrm{buf}}}\right)\right| \big/ \overline{WIP^{1}_{\mathrm{buf}}}$, where $\overline{WIP^{1}_{\mathrm{buf}}}$ corresponds to the configuration for which *No_kanbans* < *Lot_size*, **and $\overline{WIP^{2}_{\mathrm{buf}}}$ to the opposite configuration.**

We further investigated how the WIP is distributed in the system buffers. The results obtained indicate that, the higher the buffer capacity, the bigger is the difference between the average WIP per buffer and the individual average WIP in a specific buffer. This idea is supported by the values taken by the associated standard deviation when the buffer size is increased (Figure 3.11).

The individual average WIP in the middle buffers is very close to the average WIP per buffer (Figure 3.11). However, the first and last buffers in the line are under-, and overloaded, respectively, compared to the overall average WIP per buffer. This confirms the analytical results on methods of control for kanban systems obtained by Ramesh *et al.* [RPT97a, RPT97b]. They analytically proved that, for a given overall number of kanbans, the number of kanbans between machines should be unevenly distributed throughout the system so as to ensure a higher maximum permissible WIP in the middle of the line.

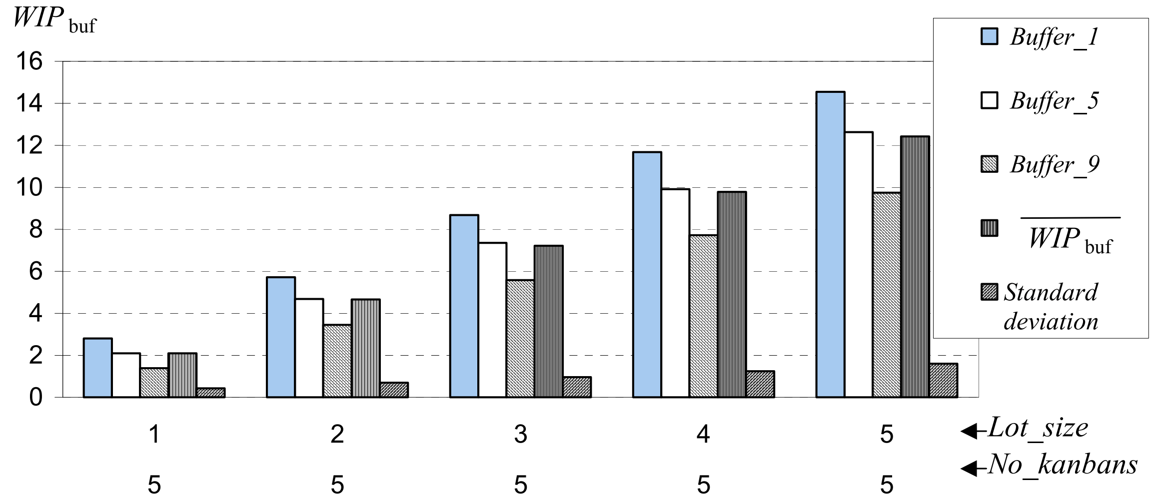

Figure 3.11 The individual and overall average WIP per buffer, and the associated standard deviation for a system with GAD and *CV*=0.5

3.3.3.2 Average WIP in the system

The average WIP in the system, denoted $\overline{WIP}$, represents the average of the total number of WIP parts in the system over the simulation interval. This measure has the same dynamic behaviour as the average WIP per buffer (see Figure 3.8). It is also interesting to represent the average WIP on machines, calculated as: $\overline{WIP_{\text{mac}}} = \overline{WIP} - \overline{WIP_{\text{buf}}}$. The values taken by this difference for processing times following GAD are represented in Figure 3.12.

The same values for the average WIP on machines are obtained analytically by using the formula:

$$\overline{WIP_{\text{mac}}} = \overline{Throughput\_rate} \times L$$

Equation 3.1 The Average WIP on the machines in the kanban system

where $\overline{Throughput\_rate}$ represents the average throughput rate and is given by Equation 3.2 below, and L represents the number of machines.

$$\overline{Throughput\_rate} = \frac{Throughput}{Simulation\_time}$$

Equation 3.2 The Throughput rate

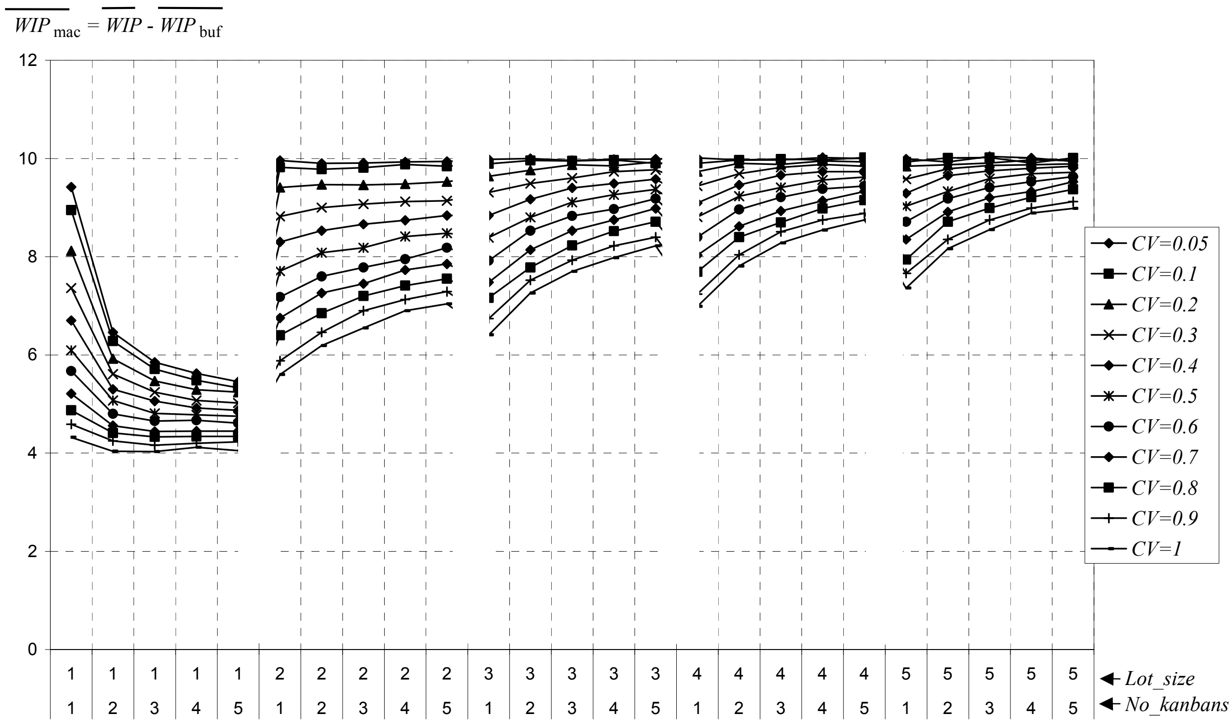

Figure 3.12 The average WIP on machines

3.3.4 The average lead time

The average lead time represents the average time that a part has spent in the system, and can be calculated using Little's Law [Kle75]:

$$\overline{Lead\_time} = \frac{\overline{WIP}}{\overline{Throughput\_rate}}$$

Equation 3.3 Little's Law for calculating the Average Lead Time

The resulting values validate the simulation results depicted in Figure 3.13.

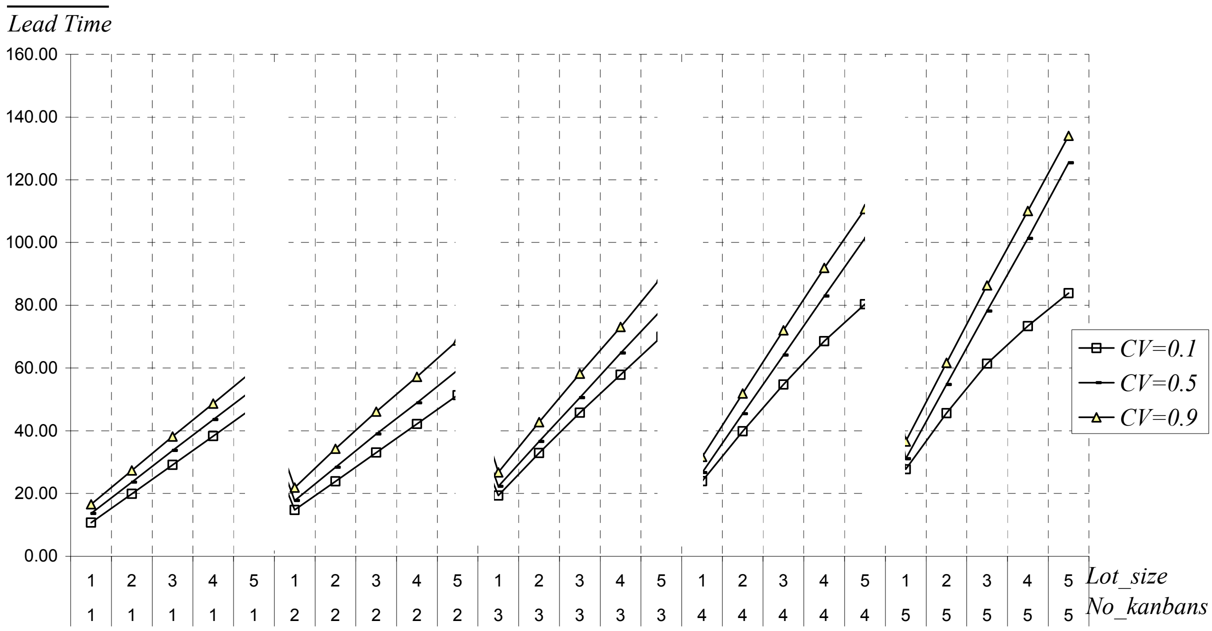

Figure 3.13 The average lead time dependence on *Lot_size* and *No_kanbans* for GAD and different *CV*s

3.4 Discussion of the effects of the initial assumptions on the results

The initial assumptions influence the simulation results as follows:

1. In the single-product approach implemented, the constraints in the system are due to the number of kanbans, the lot size, and the processing time variability. Despite the fact that simplifying assumptions (e.g. infinite input buffer; homogeneous system; a single type of product; the variability of the processing time variability alone; no labour required; no scrap, rework and breakdowns) have been used, the qualitative insights gained are still applicable to more complex systems. However, the quantitative results obtained are valid only for the

investigated configurations. A more realistic approach would need to include transportation times, cost estimates, and more products. This is, however, beyond the scope of this chapter and thesis.

2. The standard deviations in throughput and average capacity utilisation due to the choice of the set of random number streams are less than 0.5% and 0.06%, respectively, which is insignificant. They increase with the coefficient of variation. The standard deviation in average WIP per buffer and average WIP in the system due to the choice of the random number streams are less than 6%, which is more significant. This difference is alleviated by averaging the values obtained for four different sets of random number streams.
3. Since the average lead time for CV=1 is less than 140, it was considered that a warm-up period of 1000 time units is a long enough period for the transient effects to be over-passed. This ensures that the buffers are filled and the system enters a typical running status. Furthermore, by running the simulations for 10000 time units relevant figures are obtained for the performance measures.
4. In order to assess the effect of the number of sets of random number streams on the results, an analysis of the system performance for all the configurations previously investigated, GAD and 40 sets of random number streams was performed. The relative differences between the throughput values for 4 and 40 sets of random number streams are less than 1%. In absolute values this is less than 10 parts. The relative differences between the values obtained for average WIP for the two cases are less than 6%. Taking into account the fact that the average WIP takes low values, the absolute values of the differences between the average WIP for 4 and 40 random number stream sets are more relevant. These differences are lower than 0.6 parts. Furthermore, the trend followed by the average WIP in both experiments is similar. Therefore, we consider that the results obtained by averaging the figures obtained for the 4 sets of random number streams are non-specific, i.e. they have a high degree of generality. The trade-off between generality and the computational costs of the simulations is therefore successfully addressed.

3.5 An integrative analysis of the results

The analysis performed in the previous sections of this chapter showed that the full potential of the pull-type kanban systems of low inventories and reduced lead time, can be achieved only if low or no variability is embedded in the process. The concept that variability and Just-in-Time systems are incompatible is not a new one [Mon93, Sch82, SCH+95]. The current work discussed and assessed the inter-dependent issues to be considered when assessing the effect of variability on kanban systems.

The system optimization problem for system design and for system control, respectively, is defined as follows:

- System design: for a desired level of throughput and WIP, and for a given processing time variability, determine the optimal (*No_kanbans, Lot_size*) combination.
- System control: for a desired level of throughput and a given system configuration, control the variability of the system.

In Section 3.3 we investigated how the throughput, average machine utilisation, average WIP and average lead time vary individually for different coefficients of variation and system configurations. Having shown the relationship of each of these measures to *CV* and system configuration, we shall now consider how they may be combined to produce the optimal system design.

In order to achieve this objective and to illustrate the trade-off between throughput, average WIP and average lead time, these measures have been represented on the same graph in Figure 3.14.

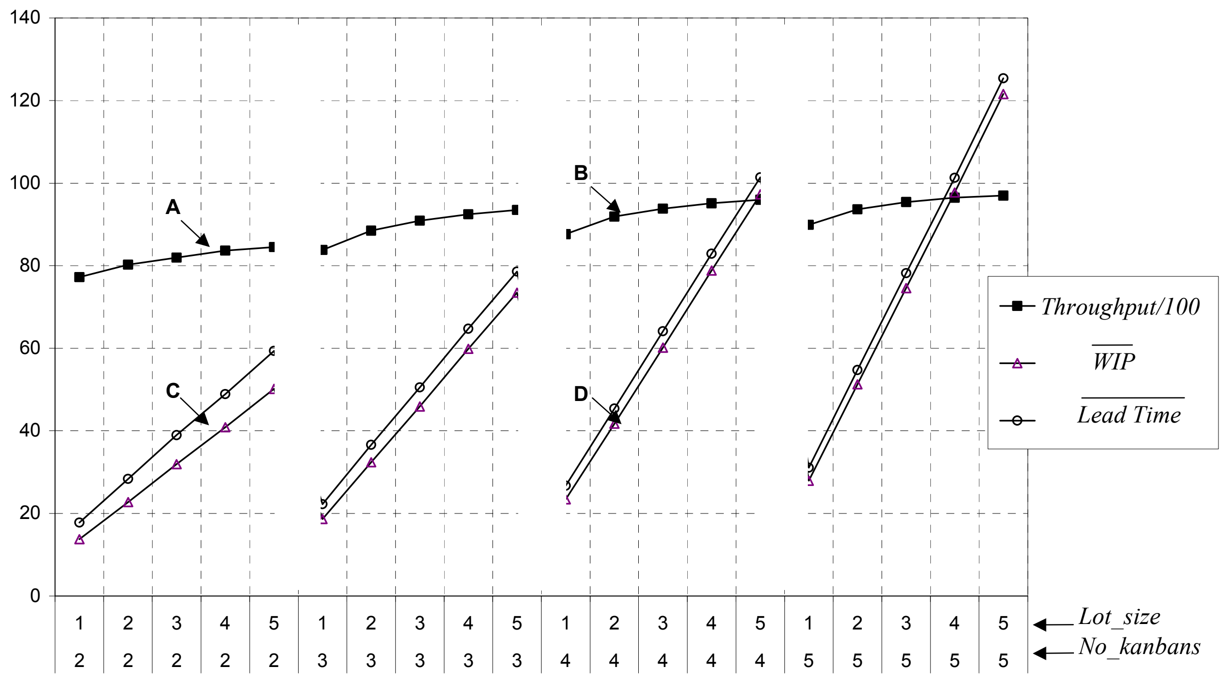

Figure 3.14 Throughput/100, average WIP and average lead time for *CV*=0.5

The graphs in Figure 3.14 indicate that in systems where variability is encountered and visibility exists*, a higher throughput leads to a higher average WIP and lead time*. The design/control problem is therefore to find the optimal system configuration that simultaneously ensures the desired levels of throughput and WIP.

The solution to this problem is straightforward for systems with no variability. However, a further analysis is required for systems characterized by variability. For the investigated system configurations, Figure 3.14 provides the quantitative answer to this problem for *CV*=0.5.

Let us now address the *No_kanbans/Lot_size* ratio problem for a fixed buffer capacity. If we choose, for example, the combinations (*No_kanbans*, *Lot_size*)=(4, 2) and (*No_kanbans*, *Lot_size*)=(2, 4), the throughput and the average WIP values are defined by the points A and C, and B and D, respectively (Figure 3.14). Although $\overline{WIP}$ has the value 41 in both cases, the configuration (4, 2) performs better because the throughput at A is 8.3*100, and at B is 9.1*100. This means a difference of no less than 800 parts between the two configurations. This choice is further reflected in the values taken by the average lead time for the two configurations, i.e. 48.9 units for the (2, 4) configuration, and 45.4 time units for the (4, 2) configuration.

Due to the very nature of the kanban systems, the configuration with 4 kanbans and lot size 2 transfers both materials and information (via kanbans) more frequently from one station to another. Hence, the machines are less likely to be idle and the work-in-process is transferred faster through the system. Increasing the number of kanbans means increasing the frequency of exchanging direct information on the system status, and thus controlling the system in a better way. On the other hand, increasing the container capacity (or the lot size) means increasing the hidden information as well as the hidden work-in-process, both of which will be transmitted through the system less frequently.

From the above analysis and the results in Figure 3.14, we conclude that the choice of the buffer capacity for a given *CV* and a desired level of throughput will ultimately depend on the relative costs of WIP and lead times. On the other hand, if two or more system configurations are characterized by the same level of average WIP, the higher throughput is obtained for the system with the higher number of kanbans.

Next, we investigate the trade-off between throughput and the average WIP in the system for different CVs.

Figure 3.15 shows that the *trade-off between throughput and average WIP becomes critical for higher CV*s. It also provides a quantitative view on the degree of improvement that would be achieved by reducing the processing time variability—a throughput increase of more than 1000 — which represents 10% of the ideal throughput level — will be obtained by reducing the *CV* from 0.9 to 0.5, for the two- and three-kanban configurations.

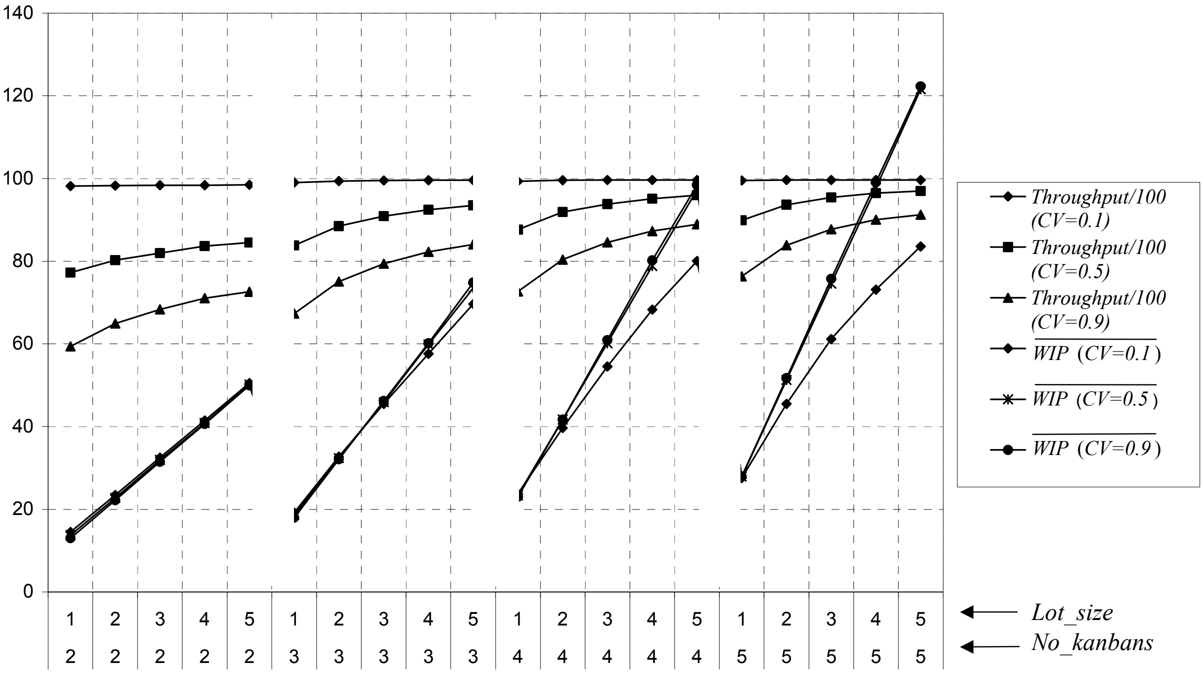

Figure 3.15 *Throughput/100* **and** $\overline{WIP}$ **for different Coefficients of Variation**

Furthermore, the choice of the direction of system optimization, in terms of changing the buffer size and/or controlling variability depends on the relationship between the costs involved in implementing the improvement and the benefits that would be thus achieved. A more realistic system design would therefore need to introduce cost estimates for WIP and material transport. By ignoring these aspects altogether, misleading conclusions can be drawn, irrespective of the investigation method used (i.e. simulation-based or analytical).

3.6 Summary

This chapter used simulation to investigate the qualitative and quantitative aspects of complexity and the mutual effects of processing time variability and of different system configurations on the performance of flow-line kanban systems. A large number of system configurations, obtained by varying both the number of kanbans between machines and the lot size, has been considered. The machine processing times have been generated employing the truncated normal and gamma distributions, a representative range of variability levels being taken into account. The throughput, average machine utilisation, average WIP and average lead time have been obtained by simulation, and the relationships between them analysed. The results have been interpreted from the point of view of the dynamic queueing behaviour, as well as from an information-exchange perspective. This provided quantitative and qualitative insights into methods of performance control of kanban systems, and into their effectiveness. The main conclusions of this chapter are presented next:

- The system performance, in terms of throughput, average machine utilisation, average WIP and average lead time, depends only on the coefficient of variation, and not on the type of processing time distribution. This extends the results obtained by Muralidhar *et al.* [MSW92], who only used average capacity utilisation as a performance measure.
- Gamma distribution has been chosen for future modelling work, as it is more realistic and computationally efficient, and provides a continuous range of values.
- Throughput and average capacity utilisation decrease significantly with an increase in the coefficient of variation.
- For a given coefficient of variation, if two or more system configurations are characterized by the same level of average WIP, the higher throughput is obtained for the system with the higher number of kanbans. This configuration ensures not only that material flows more frequently through the system, but also that information on demand and on finished jobs is exchanged more frequently throughout the operation of the system.
- Increasing the buffer size ensures an increase in both throughput and average capacity utilisation, at the expense of an increase in average WIP and average lead time. Their relative costs should therefore be considered when deciding the optimal system configuration.
- This simulation study provided a quantitative answer to the system optimization problem.

Costs related to WIP, transportation and information transmission have not been included in the current analysis. However, a discussion of the existing trade-offs has been initiated. Our results are therefore valid for systems with low transportation and storage costs relative to the production costs.

As mentioned before, the model considered in this chapter is a relatively simple one, and many simplifying assumptions have been made. Yet the level of discussions required for analysing it is far from being trivial. The complexity found in the real manufacturing world increases tremendously from pull-type to push-type systems, from Flow lines to Flexible Manufacturing Systems or job shops, where scheduling is required.

The analysis performed in this chapter sets the scene for a formal definition of complexity in manufacturing. A general framework which integrates various static and dynamic aspects of complexity in manufacturing is presented in the next chapter.

4 A conceptual and analytical framework for defining, assessing and controlling manufacturing complexity

Entities should not be multiplied unnecessarily.
Occam's Razor [OR]
Everything should be made as simple as possible, but not simpler.
Albert Einstein [Ein]

In this chapter we present a novel time-, control- and process-based framework for the information-theoretic definition, classification and measurement of manufacturing complexity. In Section 4.1, we propose a conceptual definition of manufacturing complexity from a systemic information-theoretic perspective. In Section 4.2, the control-related implications and capabilities derived from the manufacturing complexity concept are discussed, and three classes of complexity are introduced – scheduling-related decision-making (SDMC), structural (SC) and operational complexity (OC). The information-theoretic definitions of structural and operational complexity are revisited in Sections 4.3 and 4.4, and an information-theoretic definition of scheduling-related decision-making complexity is introduced in Section 4.5. Several important capabilities of SC, OC and SDMC are presented in Section 4.6, and the chapter concludes with a summary in Section 4.7.

The formal definitions of manufacturing complexity and complexity classes proposed in this thesis represent the outcome of an extensive and much enjoyed quest, that aims to address the research questions presented in Section 1.2. for a generic complex manufacturing system.

The steps and methods used in developing this framework include literature review, case studies, modelling and simulation, and information-theoretical modelling. This complexity framework also represents a sound platform and starting point for innovative research directions, which are presented in Section 7.2.

4.1 A systemic information-theoretic definition of manufacturing complexity

The static and dynamic characteristics of a manufacturing system and the relationships among individual factors determine the level of complexity within a manufacturing system. The elements contributing to the manufacturing complexity include:

1. *The people*, with their individualities, different skills and personal lives;
2. *The resource structure* - number and types of resources, layout, set-up and cycle times, maintenance tasks, idle time;
3. *The product structure* - number of different products, and for each product: number, type of resources and operations required to produce it; lead and cycle times, lot sizes;
4. *The planning and scheduling functions*, with three components:
   - The planning and scheduling strategies used;
   - The number, content, timing and priority of the documents and information used for planning and scheduling (the information flow);
   - The scheduling decision-making process;
5. *The volume, structure, content and dynamics of communications*: *internal* (during the decision-making process, team working), *intra-plant* (with other departments), and *external* (with suppliers and customers);
6. *Performance measures*; the performance measurement system adds to the overall costs, and needs to be managed. If properly defined, it will be value adding.
7. *Variability and uncertainty*:
   - *Internal:* resource breakdowns, absenteeism, data and information inaccuracy and unreliability, and quality problems.
   - *External:* customer changes, unpredictable markets, customisation, inaccurate or unreliable information and faulty raw materials.
8. *Other functions within the organisation* (such as long-term strategic plans, training, politics, and culture).

The above aspects of manufacturing complexity capture the components of a generic manufacturing system, as defined in Figure 2.2. There is a high potential for inter-dependence and connectivity between the components of the complexity: each element can depend on and influence the others. Furthermore, shared resources and concurrency are fundamental characteristics of modern manufacturing, in planning, scheduling and production. These features are premises for a highly complex system even in a deterministic environment. The variability and uncertainty specific to the real-world manufacturing environment further contribute to the increase in the number and type of potential problems.

The major understanding underlying the approach in this thesis is that manufacturing is about the integration of material, information and money flows. Materials cannot move around the factory unless a decision has been made about them. The quality of these decisions and the reliability of the information accompanying them are essential. This understanding is reflected in the definition of complexity and of the classes of complexity proposed in this thesis.

The level of awareness of the sources of complexity within a manufacturing system, and the methods used for removing or better controlling these sources, directly influence the level of performance. In characterising the complexity of a manufacturing system we distinguish between the *off-line complexity* and *on-line complexity*. The *off-line complexity* was deliberately introduced in the system design and planning phases. The *on-line complexity* is due to demand changes, breakdowns, or delays in the production process, and to the extra decision-making, resources and buffers introduced in order to deal with them. Both *off-line complexity* and *on-line complexity* have structural and operational dimensions. The *on-line complexity* could be further classified as *planned* and *unplanned complexity*. The *on-line planned complexity* refers to the informed acceptance of a certain level and type of variability and uncertainty, such as customer changes within clearly defined upper and lower tolerance levels, or unavoidable quality problems specific to high technology products and processes. *The on-line unplanned complexity* refers to resource breakdowns, absenteeism, unreliable and inaccurate information and deliveries, poor quality material [CEBS98, CES+00].

A formal definition of the concept of manufacturing complexity that integrates the above characteristics of manufacturing systems is presented below. The contribution of this definition consists of a first ever acknowledgement and integration of all the essential contributors to manufacturing complexity, seen in relationship to each other. By doing this, the definition institutionalises the manufacturing complexity concept and moves the knowledge on how manufacturing complexity can be managed and utilized towards a company's or supply chain's benefit further.

Definition 4.1 Manufacturing complexity is a systemic characteristic that integrates several key dimensions of the manufacturing environment: structural aspects (size, variety and concurrency of both products and resources), decision-making (objectives, information and control), dynamic aspects (variability and uncertainty) and goals (cost and value).

Size refers to the number of entities of each type, either structural or operational. Examples of entities include resources, information channels or products.

Variety represents a static concept that integrates the number of different classes of entities and, within each class, the various types of entities it contains. Examples of variety-related classes include machines, tools, products and communication channels.

Concurrency exists in two forms: resource concurrency and task concurrency. Resource concurrency refers to one product requiring more than one resource at a given manufacturing stage. Task concurrency refers to more than one product being produced within the system at the same time.

Objectives represent any formal or informal targets established for a system, such as the types of products, the time and quantity required at a given stage, or a certain level of performance. Although the quality and thoroughness of a given objective are assumed, it is often the case that a subjective or based-on-limited-information objective provides an inaccurate representation of the problems. On the other hand, unachieved objectives are a good starting point for identifying a problem.

Information refers to the formal and informal data, knowledge and expertise transmitted and utilised through the system. The main features of information include: accuracy, relevance, timeliness, comprehensiveness, accessibility, format and dynamics [HLW99, KLL92].

Variability refers to measurable variations between the expected and actual behaviour of the entities in the system, such as variable processing times, or variable level of product quality.

Uncertainty represents a dynamic concept, which refers to real life aspects that are difficult to predict such as breakdowns, absenteeism, and poor quality of material or information. These characteristics make the schedules unachievable or difficult to achieve, and the manufacturing system unpredictable or difficult to predict. The potential effects of the uncertainty can be counteracted by the use of spare resources and buffers, and by an increase in the monitoring and decision-making frequency.

Control refers to any action, such as decision-making, planning and scheduling, and decision implementation, taken for bringing the actual system behaviour closer to the expected behaviour

Cost refers to any costs incurred in the manufacturing system. Every time an action is taken a cost is generated, be that action decision-making, information gathering, or operating a machine. Whilst most of the production costs are generally considered and relatively transparent, the information processing costs are often ignored.

Value refers to the value added to the final product by any activity. Adding value is a complex, sometimes hidden process. Manufacturing processes directly add value to products, whereas information processing indirectly adds value to products. Potential value only becomes achieved value when a product is sold. Traditional approaches to defining the added value consider that only production adds value, while information processing represents overhead costs.

As presented in Section 2.8, previous work on the definition and measurement of manufacturing complexity has only considered clustered dimensions of complexity incorporated in Definition 4.1, such as size and variety, objectives, or variability and uncertainty [Des93, DTB92, DTB98, ETS+99, Fri95, FS01]. This definition of manufacturing complexity identifies several new key dimensions: concurrency, control, cost and value, and states that the overall manufacturing complexity is the result of the interactions and cause-effect relationships between all these dimensions.

Individual or joint dimensions of manufacturing complexity are associated with various aspects of customer satisfaction. For example, the size and variety will determine a system's ability to increase its product range and its ability to deal with customer changes. From the customer's perspective, the objectives specify the customer requirements, and the control dimension refers to the planning, scheduling and monitoring functions. Decisions need to be made each time deviations from expected or desired behaviour are detected. The quality and frequency of these decisions will have a direct impact on the system performance and on customer satisfaction. All the dimensions of manufacturing complexity need to be documented through accurate, timely, comprehensive and relevant information. Failure to meet this condition will also impact on customer satisfaction.

The dimensions of manufacturing complexity are observable and measurable, and are strongly connected to information. The definition of manufacturing complexity provided in this thesis is therefore geared towards using measurement and analysis for better system understanding, performance and control. The manner in which this conceptual definition of manufacturing complexity can be utilised to enhance the performance of a system is presented in the next section.

4.2 The utilisation and control of manufacturing complexity

The complexity definition proposed in Section 4.1 provides a systemic-based understanding of the qualitative cause-effect relationships in manufacturing. Key competencies such as flexibility and high levels of customer satisfaction can thus be achieved by an informed control of the various aspects of complexity. A system is in control when it adheres to the predictions and expectations about its behaviour, and it meets its goals.

The approach to the understanding, definition and measurement of manufacturing complexity taken in this thesis is process-based and problem-oriented. The process-based aspect refers to production-related activities such as decision-making, scheduling, information-transmission, production and performance measuring. The problem-oriented characteristic refers to the need to identify a problem before performing any complexity measurement and analysis task. Classes of problems include jobs difficult to schedule, unreliable resources, material or information, customer changes and poor customer satisfaction. A problem occurs every time the system is not in control.

An important insight achieved whilst in the process of developing the manufacturing complexity framework presented in this thesis is that *a general, global multi-purpose methodology capable of measuring all manufacturing complexity aspects is difficult,* (*if not impossible*) *to define.* The motivation for this statement resides in the variety of inter-connected, inter-disciplinary and human-related aspects that manufacturing entails. The understanding advanced by this thesis is that while specific aspects of manufacturing can be identified and measured, measuring the whole system in all its aspects has so far been infeasible. Instead, this thesis proposes a *time*-, *control*- and *process*-based hybrid approach to the definition and classification of complexity in manufacturing in three categories: scheduling-related decision-making complexity, structural complexity and operational complexity. The algorithmic complexity of converting the input information in the schedule is not discussed in this thesis. Building on previous entropic based approaches to complexity and flexibility in manufacturing [Ben92, Des93, DTB92, DTB98, FW95, Fri96, Fri98, Yao85, YP90], we define, quantify and integrate these classes of complexity through information-theoretic methods. The structure of each class of complexity and the relationships between them is presented in Figure 4.1.

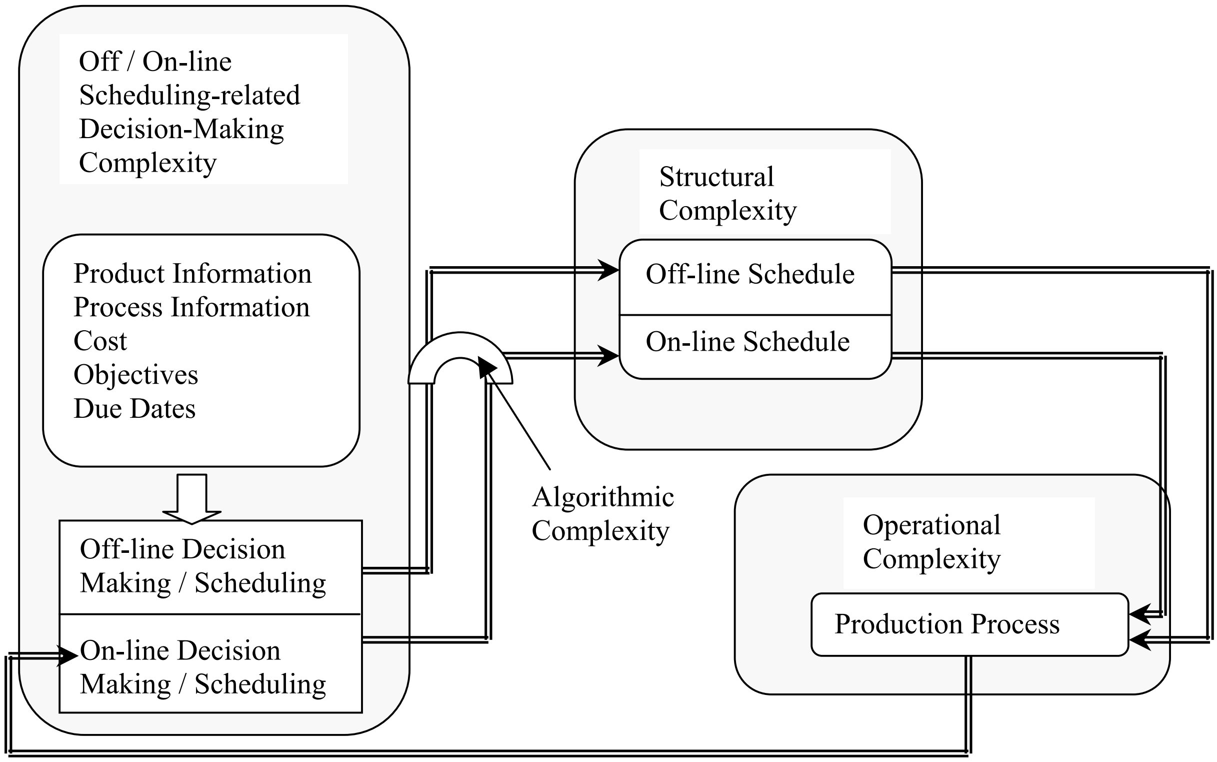

Figure 4.1 The structures of and the interactions between the classes of complexity

Figure 4.1 provides a global view of the reasons for which a static versus a dynamic definition and classification of complexity in manufacturing is not complete. First, before production can even start, a schedule needs to be created. This is made by integrating all the static information on the product, process, customer demands and company objectives through the decision-making and scheduling process, with the aim of generating a valid schedule for a given schedule horizon. In a completely predictable and reliable environment, the off-line created schedule would represent the only document to be used in the production stage. However, control by means of rescheduling is often used in order to cope with internal or external disturbances such as customer changes, unreliable machines or poor quality [BCES97, Ber97, Cal97a, ESC98, Fri98, FW95, GC89, HESC01b, IR94, SW96]. The frequency of these events and the resources required for decision-making motivate the need for a measure of the additional levels of complexity due to on-line decision-making.

Another important aspect of the complexity framework presented in this thesis is that, when properly controlled, complexity could be an adding-value asset. Greater levels of controlled complexity can mean flexibility, increased customer satisfaction and higher product variety. Therefore, complexity is not necessarily a negative feature. There are costs and value associated with it. When the system is in control, the added value outweighs the costs of managing complexity. This also means that even unplanned complexity can be value adding, if it is aimed at satisfying a customer who would reward the effort thus made.

Furthermore, as the three classes of complexity presented above capture different, significant, inter-connected aspects of manufacturing, all of them must be considered in order to obtain a comprehensive representation of complexity in manufacturing. Throughout the thesis, it is considered that the number of resources and the number of states at each resource are finite. The analytical definitions of structural and operational complexity have been provided independently by Frizelle who used a queueing approach [Fri95, Fri98, FS02], and Efstathiou using an information-theoretic approach [ECK+02, ECS+01]. The structural and operational complexity will be defined, their formulae revisited, and their capabilities discussed in Sections 4.3 and 4.4. The conceptual and analytical definitions of scheduling-related decision-making complexity are provided in Section 4.5.

4.3 Structural complexity

Intuitively, a system's structural complexity represents the difficulty of monitoring the status of that system when its states obey the schedule. In this section, a conceptual definition of structural complexity is proposed, and the information-theoretic formula for structural complexity is discussed. Its powerful and flexible capabilities are also examined.

4.3.1 Structural complexity: conceptual and analytical definitions

Definition 4.2 Structural complexity represents the expected amount of information required to define the state of the system for a given period, based on the information in the schedule.

SC is therefore a static measure created based on the schedule, which only considers the planned states at each resource. A schedule is a description of the states of a manufacturing facility at any given time, for an expected time interval called the schedule horizon. Given a schedule or set of schedules for a facility, it is possible to obtain a list of the states for each resource, and to estimate the probabilities of each state occurring at a specific resource. The level of detail embedded in a schedule depends on the level of control to be exerted on the scheduled system in the operational phase. A minimal level of detail would include a sequence of products, their associated lot sizes, and the resources on which each operation of each product is supposed to run. However, many schedules do not provide all the information required for the definition of the structural complexity, and extra information on the facility and its products may be necessary. Examples of such information are resource- and product-specific processing and set-up times, or labour skills. In many cases, the scheduler's expertise is essential for creating and maintaining a feasible schedule [MSB95a, MSB95b].

Next, we shall briefly revisit the formula for SC and discuss the measurement-related issues in relation to its capabilities.

Consider a manufacturing system with $r \geq 1$ resources. Within the assumption of stationarity, if the k -th resource ($1 \leq k \leq r$) has s_k possible states, then the structural complexity associated with that resource, $H_{SC}(k)$, is given by Efstathiou *et al.* [ECS+01,ECK+02] and Frizelle [Fri95, Fri96, Fri98]:

$$H_{SC}(k) = -\sum_{j=1}^{s_k} p_{kj} \log p_{kj}$$

Equation 4.1 The Structural Complexity of resource ***k***

where p_{kj} is the probability of resource k being in state j. Due to the properties of entropy (Section 2.7), and assuming that the events at one resource are independent of the events at any other resource, then the expected amount of information for all resources within the facility is calculated as:

$$H_{SC} = -\sum_{k=1}^{r} \sum_{j=1}^{s_k} p_{kj} \log p_{kj}$$

Equation 4.2 The Structural Complexity of the system

4.3.2 Structural complexity: Utility, meaning and methodological issues

Based on the experience accumulated through literature review, case study and theoretical modelling, this thesis extends the previous work on the definition, meaning and measurement of SC in several major directions:

1. *Application domain.* Equation 4.1 can be applied to any entities within a system for which a schedule can be drawn, such as machines, people (possibly job-specific, i.e. schedulers, operators), specific work centres – work-in-progress areas, interfaces and materials.
2. *Level of detail*. The level of detail in defining the states depends on the issue to be investigated, and should be closely linked to the states expected to be observed in the operational stage. Examples of planned states at a given resource include:

i. Running, Set-up, Maintenance, Idle.

ii. Running product A, Running product B, Set-up product A, Set-up product B, Idle,

where the two cases are differentiated by the level of detail considered when defining the states.

3. *Analysis interval*. The period for which the structural complexity is to be calculated is determined by:
   - The problem to be investigated;
   - The dynamics of the system investigated, that is the frequency of state changes;
   - The time period for which historical data is available;
   - The costs and resources required for observing the system – the structural complexity will be used by comparison with the operational complexity, in order to detect differences between the expected behaviour and the actual behaviour.
4. *Utility and meaning*. Meaningful and useful ways of calculating the structural complexity include:
   - Calculate structural complexity for the same time period as the operational complexity and on comparable bases, i.e. using the same level of detail;
   - Calculate the global structural complexity for all the historical data available;
   - Calculate structural complexity for specific time intervals, if the problem to be investigated requires this. An example of such a problem is the comparison of the variations in system complexity for different time intervals, occurred due to the introduction or removal of products, resources, or states at given resources.
5. *Result interpretation and analysis*. Possible comparisons and analyses based on the structural complexity include:
   - Temporal-based comparisons between the SC of a facility for a given period and for all the historical data available, in order to identify and assess changes in the system at different moments in time.
   - Comparisons of the SC values for different time intervals relevant for the organisation.

- Comparisons of resource-specific SC levels in order to identify potential bottlenecks and under-loaded resources. This represents a means for assessing the feasibility and quality of the schedule.
- Investigation of the relationship between SC levels and specific target values of classical performance measures, such as expected machine utilization or average lead time.

The basic assumption made in calculating the structural complexity is that an off-line created schedule exists for a period up to the scheduling horizon. This assumption is not met in systems that use only on-line real-time scheduling. In this case, the off-line SDM and control complexities are integrated in the on-line SDMC. The SC for such systems can be calculated only when the information on the expected behaviour becomes available. As SC provides a measure of the ideal expected amount of information required to define the state of a system, there is still benefit in calculating the structural complexity even after the production phase has taken place. The measure thus obtained can be correlated with the OC measure, and used to assess how closely the system's actual behaviour matches its expected behaviour. These features are discussed in the next section.

4.4 Operational complexity

The underlying motivation for a definition and measure of operational complexity comes from the necessity to identify the system's deviation from the expected behaviour, and the difficulty to monitor its status in the operational phase in order to gain this information. In this section, a conceptual definition of operational complexity is proposed, and the information-theoretic formula for operational complexity is revisited and discussed. Its ability to identify and quantify issues and cause-effects relationships is also examined.

4.4.1 Operational complexity: conceptual and analytical definitions

Definition 4.3 Operational complexity represents the amount of information required to define the state of the system, based on monitoring the system for a given period.

Operational complexity is related to the monitoring of planned and unplanned events. It captures various aspects of manufacturing systems such as size, variety, concurrency, objectives, information, variability and uncertainty. Operational complexity quantifies the additional level of information required to define the state of the system when it deviates from the expected behaviour.

The expression for operational complexity as derived by Frizelle [Fri95, Fri96, Fri98] and Efstathiou *et al.* [ECK+02] is given in Equation 4.3, and has two parts. The first term quantifies the amount of information needed to state whether the system's behaviour obeys the schedule. The next two terms quantify the amount of information needed to express the state of the system when it deviates from the schedule. The set of scheduled states and the set of non-scheduled states are disjoint.

$$H_{OC} = \left[-P \log P\right] - \left[(1-P)\log(1-P) - (1-P)\sum_{k=1}^{r} \sum_{j \in NS} p_{kj} \log p_{kj}\right]$$

Equation 4.3 The Operational Complexity (I)

In Equation 4.3 P represents the probability that the system is in control, r represents the number of resources in the system and NS represents the set of non-scheduled states that were observed and measured in the operational stage. In this case, the probabilities are calculated over the non-scheduled states,

When a single *In Control* state is defined (Equation 4.3) can be reformulated as:

$$H_{OC} = -\sum_{k=1}^{r} \sum_{j=1}^{s'_k} p'_{kj} \log p'_{kj}$$

Equation 4.4 The Operational Complexity (II)

The definition of operational complexity given in Equation 4.4 is equivalent to the definition of structural complexity (Equation 4.2), but in this case, the probabilities are those that are actually measured in practice, rather than those estimated from the schedule. This is denoted by the use of p' rather than p. Similarly, the number of states s'_k that are actually observed on each resource will differ from that in the schedule, since unscheduled states such as breakdown and awaiting resources, may occur.

4.4.2 Operational complexity: Utility, meaning and methodological issues

The utility, meaning and measurement issues related to OC have been extended in several major directions:

1. *Application domain.* Equation 4.3 and Equation 4.4 can be applied to any entities within a system in the operational stage. This includes machines, people (possibly job-specific, i.e. schedulers, operators), specific work centres – work-in-progress areas, interfaces and materials.
2. *State definition*. The state domain for the operational stage is redefined to allow for on-line decision-making. Thus, the *Planned* and *Unplanned* states are extended to three possible classes of states for measuring and calculating operating complexity:
    - *In Control & Planned* – the resource obeys the schedule or the expected behaviour.
    - *In Control & Unplanned* – the resource does not obey the off-line schedule or the expected behaviour, but is *In Control*. An on-line decision was made which scheduled the current state for this resource (i.e. non-scheduled *Make* states). This class of state

accounts for the flexibility embedded in the system and actually used in the operational stage.

- *Not in Control* & *Unplanned* – these types of states have not been scheduled at any point of the manufacturing process.

When no flexibility is allowed in the system, the occurrences of the *In Control* & *Unplanned* state will disappear. The system must be observed prior to starting the measurements in order to identify (depending on the problem and areas to be investigated): the entities to be monitored, their relevant states, and the frequency of sampling.

3. *Level of detail*. The level of detail in defining the states depends on the issue to be investigated, and should be closely linked to the states expected to be observed in the operational stage. Examples of states at a given resource include:

- *In Control & Planned*:
    - Make, Idle.
    - Make Product A (according to the schedule)
- *In Control & Unplanned*:
    - Make Product B, not on the schedule
    - Make Product B earlier or in a different quantity than scheduled
- *Not in Control & Unplanned*:
    - Machine Breakdown
    - Material Unavailable

The state definition should capture the critical states in relation with the problem to be investigated. In addition, for comparison purposes, the same level of detail in defining the states should be used when calculating the SC and the OC.

4. *Monitoring and analysis interval*. The period for which the OC is calculated is determined by:

- The problem to be investigated;
- The dynamics of the investigated system, i.e. the frequency of changing states;

- The time period for which reliable operational data, at the required level of detail, is available;
- The costs and resources required for observing the system;

The system should be monitored at a time which allows best the identification and assessment of the problem addressed. A representative behaviour should ideally be aimed for. The length of the measurement phase will depend on the cost of measurements: if this is done by external assessors, by the company itself, and how disruptive the measurements are for the process. The minimal measurement interval should ensure that a sufficient number of relevant states for the problem to be investigated are observed. The frequency of sampling should also be decided as a trade-off between the frequency of occurrence of relevant events and the cost of measurements. Ideally, measurements should be taken every time an event takes place. The next ideal stage would be to measure the system every time an event takes place at any of the relevant resources chosen for the measurements.

5. *Measurements.* During the measurement period as much information as possible on the system should be collected: schedules, schedule and resource changes, and performance measures. In addition, every time a variation is observed between what was expected to happen and what has actually happened, the reason for this variation should be identified. This information will be used to link the quantitative results with cause-effect relationships such as scheduling factors, inaccurate information, unreliable processes or suppliers, as well as with the existing values of the company-used performance measures. The relevant sources of variability and uncertainty should be identified prior to starting the measurements, and the key data collection points decided.
6. *Utility and meaning*. The operational complexity measurement process is very insightful from its observational stage – preliminary information on the type of non-scheduled states that occur and the possible reasons for their occurrence is identified. Thus, cause-effect relationships related to deviations from the expected behaviour are identified, analysed and assessed. The ultimate value of the OC metric is its applicability to the measurement of the extent and dynamics of any variations between the expected and actual behaviour.

Temporal and quantitative variations between the expected and actual behaviour for the material, information and money flows can be measured. Furthermore, individual results can be integrated for a comprehensive picture of the system behaviour, and potential directions for improvement can be identified and assessed.

7. *Result interpretation and analysis*. Possible comparisons and analyses based on the OC, or the joint operational-structural complexity include:
   - Temporal-based comparisons between the operational complexity of the facility for a given period and for all the historical data available, in order to identify and assess system changes at different moments in time.
   - Comparisons of the values, structures and reasons associated with the system's operational complexity for different time intervals relevant for the organisation.
   - Comparisons of resource-specific operational complexity levels, in order to identify operational bottlenecks and under-loaded resources.
   - Investigation of the relationship between operational complexity levels and specific target values of classical performance measures, such as expected machine utilization, average lead time and customer satisfaction.

4.5 Scheduling-related decision-making complexity

The concepts and measures for SC and OC have been presented in the previous two sections. In order to obtain a complete picture of manufacturing complexity as defined in Section 4.2, this section proposes a conceptual and analytical model of scheduling-related decision-making complexity.

Scheduling-related decision-making (SDM) represents an important aspect of any system that contains task scheduling. The underlying rationale for a definition and measure of scheduling-related decision-making complexity (SDMC) is the requirement to assess the complexity of creating a schedule that satisfies a given set of constraints (off-line SDM), and the complexity of controlling a system when it deviates from the expected behaviour (on-line SDM).

SDMC represents a systemic characteristic that arises from the mutual impact of the product structure and customer demands on the facility and on its resources. SDMC bridges the gap between structural and operational complexity. This section presents a novel, powerful definition of SDMC.

4.5.1 Scheduling-related decision-making complexity: conceptual definition

Definition 4.4 Scheduling-related decision-making complexity represents a measure of the volume and structure of the information that needs to be taken into account when creating the schedule for a given period, or, equivalently, a measure of the difficulty embedded in creating the schedule.

Off-line scheduling-related decisions are taken before the processing has started. *On-line* SDM is used to cope with the variability and uncertainty in manufacturing, or to maximise the use of the embedded flexibility in the system for a given period. Therefore, SDMC may be either a static or a dynamic measure, depending on the stage at which decisions are made (i.e. prior to starting the production process, or during the production process).

Off-line SDMC only considers planned events, whereas *on-line* SDMC may consider both planned and unplanned events. *Off-line* SDMC integrates fundamental manufacturing dimensions including size, variety, concurrency, objectives, information, and possibly cost and value. *On-line* SDMC includes all these, as well as variability and uncertainty.

4.5.2 System specification

The analytical framework for the definition of SDMC has been derived by building, extending and integrating on Deshmukh's [Des93, DTB92, DTB98], Efstathiou's [ECS+01, ECK+02], Frizelle's [Fri95, FW95, Fri96, Fri98] and Yao's [Yao85, YP90] work on complexity (Section 2.8.

The SDMC measurement method presented in this thesis considers systems with the following characteristics:

1. More than one product type may be produced in a single production run (Product flexibility).
2. A product may require multiple operations, but only one operation of a given type. An operation represents any task that needs to be performed in the production process, such as cut, form or drill.
3. An operation may require different processing times on different resources (Processing time flexibility).
4. Each operation, for a given product type, may have multiple resource options (Resource flexibility).
5. The set of operations needed to produce a given part type may or may not have precedence constraints (Sequence flexibility).
6. An operation may require more than one resource (Resource concurrency).
7. More than one resource of a specific type may be present in the system.
8. A given product demand may be met through various lot sizing strategies (Lot flexibility).
9. A resource may require set-up for a given operation and a given product, depending on its current state (Sequence-dependent set-up flexibility).
10. A set-up operation for a given operation, product and resource may require different times, depending on the resources used for set-up (Set-up time flexibility).
11. Certain raw materials or intermediate processing components may be required for more than one product type (shared materials and/or intermediate processing components).
12. Several products of the same type may be required as inputs for a given operation.
13. Assembly and disassembly operations may be present in the system.

This set of characteristics represents a more accurate and realistic representation of manufacturing systems than those considered in the previous approaches. Whilst the features 1 to 5 have been considered and modelled by Deshmukh [[Des93, DTB92, DTB98], modelling the features 6 to 13, and the assessment of their effects on SDMC represent contributions of this thesis.

4.5.3 Prerequisites to the definition of scheduling-related decision-making complexity

The analytical definition of SDMC is presented in section 4.5.4. Prior to doing this, however, the prerequisite mathematical concepts and notations and the SDM features modelled are introduced in this section. The notations in Table 4.1 are used in the thesis in relation to SDMC.

Table 4.1 SDMC related notations

Notation	Description	Remarks
$n \geq 1$	Number of products	
$r \geq 1$	Number of resources	
$m \geq 1$	Number of processing operations	
$2m$	Number of (processing and set-up) operations	Operations $m+1$, $m+2$, …, $2m$ are set-up operations for the processing operations 1, 2, …, m
$l,\ 1 \leq l \leq n$	Product	$l_1, l_2, \ldots$ also denote products
$k,\ 1 \leq k \leq \mathrm{r}$	Resource	$k_1, k_2, \ldots$ also denote resources
$\mathbf{k},\ \mathbf{k} \subseteq \{1,\ 2,\ \ldots,\ r\}$	A subset of resources	$\mathbf{k}_1,\ \mathbf{k}_2, \ldots$ also denote subsets of resources
$i,\ 1 \leq i \leq 2m$	Operation	$i_1,\ i_2, \ldots$ also denote operations
$B_l \geq 1$	Number of batches for product l	

$b \geq 1$	Batch	b_1, b_2 also denote batch indices
$Q_l \geq 1$	Demand for product l for the given schedule horizon	
$q_{il} \geq 1$	Demand per batch for product l at operation i	
$L_{il} \geq 1$	Lot size for operation i of product l	Number of times operation i has to be run in order to produce q_{il} outputs
$\mathbf{S}$	The set of possible processing states, i.e. the set of all $(i, \mathbf{k}, l)$ such that operation i of product l can be processed on resources in $\mathbf{k}$	Typically, not all elements $(i, \mathbf{k}, l)$ are possible states
$\phi(i, \mathbf{k}, l) > 0$	Processing time for operation i of product l on resources in $\mathbf{k}$	$(i, \mathbf{k}, l)$ is a possible state from $\mathbf{S}$
$\gamma(i_1, l_1, b_1, i_2, l_2, b_2) \in \{0,1\}$	Precedence requirement: 1 if operation i_1 of batch b_1 of product l_1 has to precede operation i_2 of batch b_2 of product l_2; 0 otherwise	i_1 is an operation of product l_1 and i_2 is an operation of product l_2
$s(i_1, k, \mathbf{k}_1, l_1, i_2, \mathbf{k}_2, l_2) \in \{0,1\}$	Set-up requirement: 1 if a set-up operation is required for resource k in $\mathbf{k}_1$ from operation i_1 for product l_1 to operation i_2 for product l_2 on resources $\mathbf{k}_2$; 0 otherwise	$(i_1, \mathbf{k}_1, l_1)$ and $(i_2, \mathbf{k}_2, l_2)$ are possible states from $\mathbf{S}$; i_1 is a processing or set-up operation, and i_2 is a processing operation

$st(i_1,k,\mathbf{k}_1,l_1,\mathbf{k}_2,i_3,\mathbf{k}_3,l_3) > 0$	Set-up time of resource k for processing operation i_3 on resources $\mathbf{k}_3$ and product l_3, when the previous operation on this resource was operation i_1 on resources $\mathbf{k}_1$ for product l_1, with resources $\mathbf{k}_2$ being used for set-up	Defined when set-up is required, i.e. $s(i_1,k,\mathbf{k}_1,l_1,i_3,\mathbf{k}_3,l_3) = 1$ Resource k has to belong to all resource subsets $\mathbf{k}_1$, $\mathbf{k}_2$ and $\mathbf{k}_3$
$\pi(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4) \geq 0$	SDMC-contributing factor for operations i_1, i_2, i_4, Resources k, k_2, k_4, resource subsets $\mathbf{k}_1$, $\mathbf{k}_2$, $\mathbf{k}_3$, $\mathbf{k}_4$, and products l_1, l_2, l_4	Represents a set-up or total processing time, as described in Section 4.5.4
$\tilde{\pi}(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4) \geq 0$	Normalized SDMC-contributing factor	

4.5.3.1 The product set

The information necessary for the definition of the product set and the lot sizing strategy, i.e. n, Q_l, B_l (Table 4.1), should be available from the product and system design phase and from the schedule.

With the notations in Table 4.1, for systems with single-input single-output operations (with no assembly or disassembly operations) some particularly interesting relationships are:

- The lot sizes are not operation-specific, and therefore the total number of products l to be produced does not depend on the operation, i.e. $L_l = q_l$ and $Q_l = B_l L_l$. The impact of assembly/disassembly operations on operation-specific lot sizes and on SDMC is considered in Section 4.5.6.
- When $L_l = 1$, $Q_l = B_l$ (part-based SDM, i.e. a separate scheduling decision will be made for each product).
- When $B_l = 1$, $Q_l = L_l$ (single batch, lot-based SDM, i.e. a single scheduling decision will be made for the whole batch).

Product flexibility refers to a system's capability to process more than one product in a given schedule horizon. *Lot flexibility* consists of a system's capability to satisfy a given product demand through various lot sizing strategies. The explicit consideration of n, Q_l and B_l (Table 4.1) allow for *product flexibility* and *lot flexibility* to be modelled.

4.5.3.2 The operation set

The information necessary for the definition of the operation set for a given product set, and its size, m (Table 4.1) should be available from the product design phase.

Operations in this context are any tasks that use resources to transform raw material into finished product. Therefore, different products may require similar operations. An operation is defined by the input status of the raw material or intermediate product, and by the resources that could process it. *Operation flexibility* consists of a system's capability to perform various operations on any of several resource subsets.

4.5.3.3 The resource set

The information necessary for the definition of the resource set, and its size, r (Table 4.1) should be available from the system design phase. The information for the resource subset $\mathbf{k}$ (Table 4.1) that may be used by an operation of a product should be defined in the product and system specification phases.

Each resource is considered individually. Resources that have the same processing capabilities for all the products are deemed identical. *Resource flexibility* refers to the capability of a resource to perform more than one type of operation and/or more than one type of product.

Table 4.2 Resource classification

Classification	Capabilities	Associated specification elements	Type of processing
Processing resources	Processing operations; May need set-up	The operational requirement set (Section 4.5.3.4) The set-up requirement set (Section 4.5.3.6) The set-up time requirement set (Section 4.5.3.6)	Independent or joint, during the production process Joint (With one or more resources), during the set-up process
Set-up resources	Set-up operations only	The set-up requirement set (Section 4.5.3.6) The set-up time requirement set (Section 4.5.3.6)	Joint, with one or more resources, during the set-up process
Mixed resources (set-up and processing)	Processing and set-up operations	The operational requirement set (Section 4.5.3.4) The set-up requirement set (Section 4.5.3.6) The set-up time requirement set (Section 4.5.3.6)	Independent or joint, during the production process Joint (With one or more resources), during the set-up process)

We consider that a resource may be used for both set-up and processing operations at different moments of time. Depending on the type of operations accommodated, we can classify the resources according to their capabilities as presented in Table 4.2.

We use resource subsets to model the situation where an operation requires more than one resource for processing, i.e. resource concurrency. All the elements k in a resource subset $\mathbf{k}$ will have to be used simultaneously for processing an operation. For example, if resources 1 and 2 have to be used simultaneously for processing an operation, then $\mathbf{k} = \{1, 2\}$. When there is no such requirement, $\mathbf{k}$ has a single element.

4.5.3.4 The operational requirement set

The information necessary for the definition of the operational requirement set for a given product set and a given system, $\phi(i, \mathbf{k}, l)$ (Table 4.1), should be available from the product and system design phases.

Processing time flexibility refers to the capability to perform a given operation on various resources in different processing times. This important capability is often encountered in real manufacturing systems.

The operational requirement set models product, resource, operation and processing time flexibility, as well as concurrent requirements of resources. In other words, it models the resource-related AND and OR requirements for a given product set.

When multiple resources of the same type are present in the system, this will be reflected in the manner in which the operational requirements are defined, each resource being considered individually. Only normal processing operations (i.e. no set-ups) are considered when defining the operational requirement set.

4.5.3.5 The precedence requirement set

In the first phase only the precedence requirement elements $\gamma(i_1, l_1, b_1, i_2, l_2, b_2)$ corresponding to processing operations are initialised, i.e. for $i_1 = \overline{1,m}$ and $i_2 = \overline{1,m}$ operation indices. $b_1 = \overline{1, B_{l_1}}$ and $b_2 = \overline{1, B_{l_2}}$ represent batch indices. The extension of the precedence requirement set to include set-up precedence relationships is implemented in Section 4.5.3.7.

The information necessary for the definition of the precedence requirement elements $\gamma(i_1, l_1, b_1, i_2, l_2, b_2)$ (Table 4.1) for processing operations (i.e. $i_1 = \overline{1,m}$ and $i_2 = \overline{1,m}$) for a given product set should be available from the product design phase, and from the schedule.

The precedence relationships between two batches of a given part type will depend on the policy on the performance measures of the system (such as WIP, lead time, or waiting time). For example, if for product l a single batch is allowed in the system at any given time, this constraint is formally defined as:

$$\gamma(i_1, l, b_1, i_2, l, b_2) = 1,\ b_1 < b_2,\ \forall i_1 = \overline{1,m},\ \forall i_2 = \overline{1,m},\ b_1 = \overline{1, B_{l_1}}, b_2 = \overline{1, B_{l_1}}$$

The above relationships model the constraint that any operation for any batch b_1 of product l has to be preceded by all the operations of the batches 1 to $(b_1 - 1)$ of that product.

Sequence flexibility refers to a system's ability to process operations that have various precedence constraints. The introduction of the precedence requirement set allows the modelling of sequence flexibility and the assessment of its impact on SDMC.

4.5.3.6 The set-up requirement and set-up time requirement sets

The set-up requirement elements $s(i_1,k,\mathbf{k}_1,l_1,i_2,\mathbf{k}_2,l_2)$ and the set-up time requirement elements $st(i_1,k,\mathbf{k}_1,l_1,\mathbf{k}_2,i_3,\mathbf{k}_3,l_3)$ (Table 4.1) represent the resource-specific set-up and set-up time requirements, depending on the previous state and next states of the resource. The information necessary for defining these sets for a given product set and a given system should be available from the product and system design phases, and from the schedule.

Sequence-dependent set-up flexibility refers to a system's capability to require or not require resource set-up for a given operation and a given product, depending on the current state of the resource. *Set-up time flexibility* refers to a system's capability to require different set-up times for a resource depending on the resources used for the set-up operations. Our specification of set-up requirements and set-up time requirements allow for sequence-dependent set-up flexibility and set-up time flexibility to be modelled, and for their impact on SDMC to be assessed.

The manner in which the set-up requirements and the set-up time requirements are defined allows the modelling of both AND and OR operations for setting up a resource for a specific operation and product, and of set-up specifications that depend on the operation, product and resource set for a specific resource. Product, operation and resource flexibility are thus embedded in the model. These definitions also create the premise for introducing sequence-dependent constraints in the modelling stage. We assume that two successive set-up operations are not allowed in the manufacturing system modelled, which is consistent with the static and planned conditions usually considered in manufacturing when creating an off-line schedule. Once a resource subset has been chosen to perform the next operation, all the resources in this subset have to be set up prior to starting the processing operation, whether simultaneously or not. This representation accommodates the situation where several resources are required for setting up a resource. Moreover, the set-up time requirement set can model the flexibility of having different set-up times for a given resource depending on the resources used for set up and on the previous operation.

4.5.3.7 The extension of the precedence requirement set

For systems that contain set-up operations, the precedence requirement sets for processing operations needs to be extended to include the requirements for set-up operations. The indices in the extended definition of the precedence requirement set refer to the extended operations as defined by the set-up requirements set and the set-up time requirement set. The information necessary for the extension of the precedence requirement set is specified by the values that the operational and precedence requirement sets take for processing operations.

The rationale behind the conversion algorithm is that if processing operation i has to precede processing operation j (as defined by the precedence requirement set, Section 4.5.3.5), and if we denote the precedence requirement by the $\rightarrow$ operator, then the conversion of indices to model the sequence: *set-up* $op_i \rightarrow op_i \rightarrow$ *set-up* $op_j \rightarrow op_j$ has to be done. In the extended precedence requirement set, the indices $i_1 = \overline{1,m}$ and $i_2 = \overline{1,m}$ will continue to refer to processing operations i_1 and i_2. The indices $i_1 = \overline{(m+1),2m}$ and $i_2 = \overline{(m+1),2m}$ refer to the set-up operations for processing operations $(i_1 - m)$ and $(i_2 - m)$, respectively, and will therefore have to always precede their corresponding processing operations. Furthermore, any set-up operation i with $i = \overline{(m+1),2m}$ will only be run if its corresponding processing operation $(i - m)$ is scheduled to run. These constraints will be modelled in Section 4.5.4. The algorithm for the extension of the precedence requirement set is presented in Figure 4.2. Indentation is used to specify the body of the **For** and **If** statements in the description of the algorithm in Figure 4.2, and throughout the rest of the thesis (Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6).

For each precedence relationship between processing operations (lines 1 and 2 in Figure 4.2), the initialisation in line 3 models the fact that any precedence relationship between two processing operations, indexed i_1 and i_2 holds true for their corresponding set-up operations $(i_1 + m)$ and $(i_2 + m)$, respectively. Although this relationship only needs to be modelled for the elements of the set-up time requirement set, the time required to identify all such operations may not make the reduction in the number of elements of the extended precedence requirement set worthwhile. The trade-off between the increase in the execution time and the memory requirements represents the criterion based on which the optimal approach in addressing this issue should be decided. In this thesis, for simplicity, the initialisation in line 3 is performed for all the existing precedence relationships between processing operations.

1. For each precedence requirement element $\gamma\left(i_1, l_1, b_1, i_2, l_2, b_2\right) = 1$ **do**

2.   **If** (operation $i_1 \le m$ **and** operation $i_2 \le m$) **then**

3.   **Set** precedence requirement element $\gamma\left(i_1 + m, l_1, b_1, i_2 + m, l_2, b_2\right)$ **to** 1

4.   **For** each Set-up time requirement element $st\left(i_1^*, k, \mathbf{k}_1^*, l_1^*, \mathbf{k}_2^*, i_3^*, \mathbf{k}_3^*, l_3^*\right) \neq 0$ **do**

5.   **For** each batch $b_3 = \overline{1, B_{l_3^*}}$ **do**

6.   **Set** precedence requirement element $\gamma\left(i_3^* + m, l_3^*, b_3, i_3^*, l_3^*, b_3\right)$ **to** 1

7.   **If** (operations $i_1 = i_3^*$ **and** products $l_1 = l_3^*$) **then**

8.   **Set** precedence requirement element $\gamma\left(i_1 + m, l_1, b_1, i_2, l_2, b_2\right)$ **to** 1

9.   **Else If** (operations $i_2 = i_3^*$ **and** products $l_2 = l_3^*$) **then**

10.   **Set** precedence requirement element $\gamma\left(i_1, l_1, b_1, i_2 + m, l_2, b_2\right)$ **to** 1

Figure 4.2 The algorithm for the extension of the precedence requirement set

The next initialisation stage is performed in line 6, and models the fact that each set-up operation has to precede its associated processing operation, for all the batches of any product that require set-up operations, as defined in line 5.

Next, the extension of precedence requirements for all operations that fulfil $i_1 \to i_2$ (condition tested in line 1) to $(i_1 + m) \to i_2$ (set-up of operation i_1 has to precede operation i_2) is implemented for all operations i_1 that require a set-up (lines 4 and 7). This initialisation is performed in line 8. Similarly, the extension from $i_1 \to i_2$ (condition tested in line 1) to $i_1 \to (i_2 + m)$ is implemented for all i_2 that require a set-up (lines 4 and 9) – this initialisation is performed in line 10.

The initialisations of the precedence requirement elements in lines 6, 8 and 10 can take place more than once. In order to avoid this, a further additional test may be introduced on the value of the precedence requirement element. For simplicity, this was not introduced in the extension algorithm presented in Figure 4.2. As discussed before, the decision on whether to perform these tests depends on the additional execution costs that such tests would incur for a large number of values of the precedence requirement set.

Notice that the extension of the precedence requirement set for a non-null element $st\left(i_1^*, k, \mathbf{k}_1^*, l_1^*, \mathbf{k}_2^*, i_3^*, \mathbf{k}_3^*, l_3^*\right) \neq 0$ does not impose the conditions $i_1^* \to i_3^*$ and $i_1^* \to \left(i_3^* + m\right)$. There is no prerequisite that this situation should occur. This aspect represents a characteristic that will allow the innovative modelling of sequence-dependent set-up requirements, i.e. the fact that set-up from operation i_1^* to processing operation i_3^* is required only when $i_1^* \to i_3^*$. This modelling will be performed in Section 4.5.4.

Having analytically defined the fundamental characteristics of a manufacturing system from the SDM perspective (Section 4.5.3), the next step is to integrate these characteristics in a measure of the complex features of a manufacturing system with the properties presented in Section 4.5.2, System specification. The SDMC-contributing factor set that models these features is defined in Section 4.5.4. The SDMC measure that integrates these features in a single measure is then defined based on the SDMC-contributing factor set in Section 4.5.5.

4.5.4 The SDMC-contributing factor set

The rationale behind the definition of the SDMC-contributing factor set is to capture the classes of flexibility, the variety in job processing and set-up times, and the resource concurrency specific to complex manufacturing systems in a single complex entity. The thesis does this by considering each decision that needs to be made for creating the schedule for a given period, and by analytically modelling the number and types of options and constraints that need to be taken into account before making a decision. This conforms to the conceptual definition of the SDMC given in Section 4.5.1.

In order to calculate the SDMC, we will first define the SDMC-contributing factor $\pi\left(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4\right)$ associated with:

1. The operations i_1,i_2,i_4;
2. The resources k, k_2, k_4;
3. The resource subsets $\mathbf{k}_1$, $\mathbf{k}_2$, $\mathbf{k}_3$, $\mathbf{k}_4$;
4. The products l, l_2, l_4.

The various parameters of π have the following meaning:

- k represents the reference resource;
- $i_1,\mathbf{k}_1,l_1$ represent the previous operation i_1 on the reference resource $k \in \mathbf{k}_1$ for product l_1;

- $i_2, k_2, \mathbf{k}_2, l_2, b_2$ represent the operation currently considered for $k \in \mathbf{k}_2$ for batch b_2 of product l_2;
- $\mathbf{k}_3$ represents the resource subset that resource k will belong to during the next operation, $(i_2 - m)$, when the current operation is a set-up operation;
- $i_4, k_4, \mathbf{k}_4, l_4, b_4$ represent the alternative operation i_4 that may be considered for processing on resource $k_4 \in \mathbf{k}_4$ for batch b_4 of product l_4.

A more detailed description of these parameters is presented next:

- k represents the reference resource for which the decision is currently made. A reference resource has to be either a processing resource or a mixed resource (and never a set-up only resource), as defined in Table 4.2. This models the fact that the focus of SDM is on processing operations, and that set-up operations are considered only in relationship to the processing operations, rather than on their own.
- index 1 has been introduced in order to model sequence-dependent set-ups and refers to the previous status of the reference resource k. It therefore has two meanings, depending on whether the current operation i_2 is a set-up or a processing operation.
    - o When the current operation i_2 is a processing operation ($i_2 = \overline{1, m}$), we need to model the fact that the time of a processing operation on a processing resource does not depend on the previous operation on that resource. This is done by initialising only the π elements for which $i_1 = i_2$, and thus modelling that there is no sequence-dependence flexibility associated with processing operations. When the current operation i_2 is a set-up operation ($i_2 = \overline{(m+1), 2m}$), i_1 represents the previous operation on the reference resource k, and it may be either a set-up operation or a processing operation, therefore $i_1 = \overline{1, 2m}$.
    - o When the current operation i_2 is a processing operation ($i_2 = \overline{1, m}$), using the same reasoning steps as above, we initialise only the π elements for which $\mathbf{k}_1 = \mathbf{k}_2$. When the

current operation i_2 is a set-up operation ($i_2 = \overline{(m+1),2m}$), we initialise only the π elements for which $k \in \mathbf{k}_1$ during the previous operation, i_1.

- o When the current operation i_2 is a processing operation ($i_2 = \overline{1,m}$), using the same reasoning steps as for i_1 and $\mathbf{k}_1$, we only initialise the π elements for which $l_1 = l_2$. When the current operation i_2 is a set-up operation ($i_2 = \overline{(m+1),2m}$, l_1 represents the product index processed in the previous operation by the reference resource, k.

- index 2 refers to the current status of the reference resource k
  - o i_2 represents the current operation on the reference resource k
  - o k_2 has been introduced in order to model concurrency in the set-up phase, and therefore it has two meanings, depending on i_2. If operation i_2 is a processing operation ($i_2 = \overline{1,m}$), then we initialise only the π elements for which $k_2 = k$, and therefore k_2 does not bring any new information in the modelling phase. If operation i_2 is a set-up operation ($i_2 = \overline{(m+1),2m}$), then k_2 represents the resource that is currently being used to set-up the reference resource k for the processing operation $(i_2 - m)$.
  - o $\mathbf{k}_2$ has also been introduced in order to model concurrency in the set-up phase, and therefore it has two meanings, depending on i_2. When operation i_2 is a processing operation ($i_2 = \overline{1,m}$), then k has to belong to $\mathbf{k}_2$ for the current processing operation. If operation i_2 is a set-up operation ($i_2 = \overline{(m+1),2m}$), then $\mathbf{k}_2$ represents the resources that are currently being used to set-up the reference resource k for processing operation $(i_2 - m)$. Both resource k_2 and the reference resource k have to belong to $\mathbf{k}_2$.
  - o l_2 represents the product currently considered for processing by the reference resource k (for $i_2 = \overline{1,m}$), or for which the reference resource k is set up (for $i_2 = \overline{(m+1),2m}$).

- o b_2 represents the batch of the product which is currently processed by the reference resource k (for $i_2 = \overline{1,m}$), or for which k is set-up (for $i_2 = \overline{(m+1),2m}$). This feature allows for lot flexibility as defined in Section 4.5.3.1 to be modelled and assessed.

- index 3 refers to the next operation on the reference resource k, and is relevant only if the current operation on this resource is a set-up operation.
  - o $\mathbf{k}_3$ has been introduced in order to completely define the status for which a resource is set-up, and, similarly as for k_2 and $\mathbf{k}_2$, has two meanings, depending on i_2. When operation i_2 is a processing operation we initialise only the π elements for which $\mathbf{k}_3 = \mathbf{k}_2$, and therefore $\mathbf{k}_3$ does not bring any new information to the model. If operation i_2 is a set-up operation, then $\mathbf{k}_3$ represents the set of resources that the reference resource k will belong to during the processing operation $(i_2 - m)$ for which it is currently set-up. This index allows the modelling of the condition that a set-up operation on a specific processing resource must be followed by the execution of the processing operation itself. It is therefore not flexibility, but temporal conditioning that is modelled using this index.

- index 4 has been introduced to model the relationships of the current entity with all the other entities on which decisions need to be made, as defined by the operational requirement, the set-up requirement**,** the set-up time requirement and the precedence requirement sets. In the remaining part of the thesis, they will be referred to as alternative operations, resources, resource subsets, or products.
  - o i_4 represents a processing operation of processing batch b_4 of product l_4 on resource k_4 using the resources in $\mathbf{k}_4$, for ($i_4 = \overline{1,m}$), or a set-up operation of resource k_4 using the resources in $\mathbf{k}_4$ for processing batch b_4 of product l_4 (for $i_4 = \overline{(m+1),2m}$).

To summarize, in the definition of the SDMC-contributing factor set the reference resource k has to belong to all $\mathbf{k}_1, \mathbf{k}_2$ and $\mathbf{k}_3$. When the current operation i_2 is a processing operation

($i_2 = \overline{1,m}$), then the SDMC-contributing factors will only be initialised for $k_2 = k$, $\mathbf{k}_1 = \mathbf{k}_2 = \mathbf{k}_3$, and $l_1 = l_2$. Otherwise, the current operation i_2 is a set-up operation of the reference resource k using resource k_2 in resource subset $\mathbf{k}_2$ for performing operation $(i_2 - m)$ on set $\mathbf{k}_3$ on batch b_2 of product l_2.

The SDMC-contributing factors integrate all the options available to the scheduler in the scheduling phase, in the process of identifying what could be the follow-up operation on resource *k,* depending on the previous status of that resource and on the tasks in the schedule that are yet to be scheduled. For a given reference resource k, there are two type of decisions that have to be made:

1. What would be the next processing operation to be run on reference resource k; therefore, the variables i_2, $\mathbf{k}_2$ and l_2 need to be specified for a given k.
2. Once the next processing operation for resource k was decided, decide the resource subset to be used for its set-up, considering all the options available as defined by the set-up time set (Section 4.5.3.6).

With the system components introduced in sections 4.5.3 specified, the SDMC-contributing factors are initialised by applying the four-step algorithm described in the remainder of this section (Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6). Step 1 of the algorithm models the SDM options related to set-up operations versus set-up operations, and Step 2 models the SDM options related to set-up versus processing operations. In order to complete all the SDM options, Step 3 and Step 4 of the algorithm model the SDM options corresponding to processing operations versus processing operations, and versus set-up operations, respectively.

The SDMC-contributing factors capture the level and types of the various classes of SDM flexibility in the system. For the set-up operations versus set-up operations modelling (Step 1), and for the processing operations versus processing operations modelling (Step 3), the diagonal elements will be initialised with non-null values. These elements have the property that the indices of the alternative element are identical with the corresponding indices of the current element. Equation 4.5 formally defines the properties of the diagonal elements for a generic element $\pi(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4)$.

$i_2 = i_4$ **and** $k_2 = k_4$ **and** $\mathbf{k}_2 = \mathbf{k}_4$ **and** $l_2 = l_4$ **and** $b_2 = b_4$

Equation 4.5 The definition of the diagonal elements for the SDMC-contributing factor set

A global remark is that for all the steps, the elements $\pi(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4)$ for which $\gamma(i_4,l_4,b_4,i_2,l_2,b_2)=1$ (i.e. the alternative operation, i_4 for batch b_4 of product l_4 has to precede the current operation, i_2, for batch b_2 and product l_2) are not initialised. This corresponds to a decrease in the number of options that the scheduler has by introducing precedence constraints, and will be reflected in a reduced value of SDMC. More details about this property will be presented in Section 4.6.4. When no precedence requirements are defined between the current and the alternative operations, the decision on whether to initialise an element $\pi(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4)$ is made based on additional, step-specific conditions.

For Step 1 we need to consider all the possible options for set-up, as defined by the set-up time requirement set, in relation with each other. This is done in lines 1.1 and 1.2 (Figure 4.3). The operations, resource subsets and products that need to be considered are thus identified. In Step 1, the previous state of the reference resource *k*, the current operation, the resource subsets associated with the current and future operations, and the previous and current product for $\pi(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4)$ are calculated as a function of the parameters of $st(i_1,k,\mathbf{k}_1,l_1,\mathbf{k}_2,i_3,\mathbf{k}_3,l_3)$. The alternative operations are given by $st(i_1^*,k^*,\mathbf{k}_1^*,l_1^*,\mathbf{k}_2^*,i_3^*,\mathbf{k}_3^*,l_3^*)$.

Step 1. Modelling SDM for set-up operations versus set-up operation

1.1 For each set-up time requirement element $st(i_1, k, \mathbf{k}_1, l_1, \mathbf{k}_2, i_3, \mathbf{k}_3, l_3) \neq 0$ **do**

1.2 **For** each alternative set-up time requirement element $st\left(i_1^*, k^*, \mathbf{k}_1^*, l_1^*, \mathbf{k}_2^*, i_3^*, \mathbf{k}_3^*, l_3^*\right) \neq 0$ **do**

1.3 **For** each current resource k_2 in $\mathbf{k}_2$ **do**

1.4 $\pi(i_1, k, \mathbf{k}_1, l_1, i_3 + m, k_2, \mathbf{k}_2, \mathbf{k}_3, l_3, b_2, i_3 + m, k_2, \mathbf{k}_2, l_3, b_2) = st(i_1, k, \mathbf{k}_1, l_1, \mathbf{k}_2, i_3, \mathbf{k}_3, l_3)$

1.5 **For** each alternative resource k_4 in $\mathbf{k}_2^*$ **do**

1.6 **For** each batch of current product $b_2 = \overline{1, B_{l_3}}$ **do**

1.7 **For** each batch of alternative product $b_4 = \overline{1, B_{l_3^*}}$ **do**

1.8 **If** (precedence element $\gamma\left(i_3^* + m, l_3^*, b_4, i_3 + m, l_3, b_2\right) = 0$ **and**

(operations $i_3 \neq i_3^*$ **or** resource subset $\mathbf{k}_2 \neq \mathbf{k}_2^*$ **or** products $l_3 \neq l_3^*$)) **then**

1.9 $\pi\left(i_1, k, \mathbf{k}_1, l_1, i_3 + m, k_2, \mathbf{k}_2, \mathbf{k}_3, l_3, b_2, i_3^* + m, k_4, \mathbf{k}_2^*, l_3^*, b_4\right) =$
$st(i_1, k, \mathbf{k}_1, l_1, \mathbf{k}_2, i_3, \mathbf{k}_3, l_3)$

1.10 **Else** $\pi\left(i_1, k, \mathbf{k}_1, l_1, i_3 + m, k_2, \mathbf{k}_2, \mathbf{k}_3, l_3, b_2, i_3^* + m, k_4, \mathbf{k}_2^*, l_3^*, b_4\right) = 0$

Figure 4.3 Step 1. Modelling SDM set-up operations versus set-up operations

The previous operation on the reference resource k, operation i_1, may be either a set-up or a processing operation, depending on whether k is a processing resource or a mixed resource (Table 4.2). The sequence of events modelled is $i_1 \to i_2 \to (i_2 - m)$, where symbol $\to$ indicates precedence, as defined in Sections 4.5.3.6 and 4.5.3.7. In both initialisation stages of $\pi(i_1, k, \mathbf{k}_1, l_1, i_2, k_2, \mathbf{k}_2, \mathbf{k}_3, l_2, b_2, i_4, k_4, \mathbf{k}_4, l_4, b_4)$ in lines 1.4 and 1.9, the current operation is $(i_3 + m)$ and refers to the set-up operation of processing operation i_3. A similar meaning has the alternative operation $\left(i_3^* + m\right)$ in lines 1.8 and 1.9.

The diagonal elements defined by Equation 4.5 are initialised in line 1.4. For the initialisation of the non-diagonal elements, (lines 1.5 to 1.9), all the alternative resources k_4 in the alternative resource subset $\mathbf{k}_2^*$ are considered. This ensures that the relationships of type *set-up operations* versus *set-up operations* are modelled. The batch indices, b_2 and b_4 are calculated based on the batch number for the reference set-up operation, B_{l_3}, and the batch number corresponding to the alternative set-up operation, $B_{l_3^*}$ (lines 1.6 and 1.7). Only the elements that fulfil the following conditions will result in a π element being initialised with a non-null value (line 1.8):

- The set-up $\left(i_3^* + m\right)$ for batch b_4 of product l_3^* does not have to precede the current set-up operation considered, $\left(i_3 + m\right)$ for batch b_2 of product l_3 (therefore there is a sequence flexibility-related SDM option which needs to be modelled) **and**
- $i_3 \neq i_3^*$, i.e. the operation for which the reference resource is set-up is different than the alternative operation considered, therefore there is an operation flexibility-related SDM option which needs to be modelled, **or** $\mathbf{k}_2 \neq \mathbf{k}_2^*$, i.e. the current set of resources is different than the alternative resource subset considered (therefore there is a resource flexibility-related SDM option which needs to be modelled), **or** $l_3 \neq l_3^*$, i.e. the current product is different than the alternative product considered (therefore there is a product flexibility-related SDM option which needs to be modelled).

The fact that the term $b_2 \neq b_4$ is not included in the right term of the **If** condition in line 1.8 (within the brackets with the **or** logical conditions) models the fact that the set-up for a given operation on a given resource subset and a given product does not depend on the batch index. Therefore, when ($\gamma\left(i_3^*, l_3^*, b_4, i_3, l_3, b_2\right) = 0$ **and** $i_3 = i_3^*$ **and** $\mathbf{k}_2 = \mathbf{k}_2^*$ **and** $l_3 = l_3^*$), only the diagonal elements of the SDMC-contributing factors will be initialised for $b_2 \neq b_4$ (line 1.4) and *set-up operations* versus *set-up operations*. The sequence flexibility between various batches of a given product is modelled through processing operations in Step 3 (Figure 4.5).

Also, the fact that the term $k_2 \neq k_4$ is not included in the right term of the **If** condition in line 1.8 models resource concurrency, that is the fact that all the resources k_2 in resource subset $\mathbf{k}_2$ have to be used simultaneously for set-up for the current operation. Therefore, there is just one set-up operation (and no other option) for all the resources in $\mathbf{k}_2$.

The value that a π element takes represents the time required for setting up the reference resource k for processing operation $(i_2 - m)$ for batch b_2 of product l_2 on resources $\mathbf{k}_3$, when all the resources k_2 in $\mathbf{k}_2$ are used for set-up, and when the previous operation on k is operation i_1 for product l_1 on resources $\mathbf{k}_1$.

Step 2. Modelling SDM for set-up operations versus processing operations	
2.1	**For** each set-up time requirement element $st(i_1, k, \mathbf{k}_1, l_1, \mathbf{k}_2, i_3, \mathbf{k}_3, l_3) \neq 0$ **do**
2.2	**For** each alternative processing requirement element $\phi(i_4, \mathbf{k}_4, l_4) \neq 0$ **do**
2.3	**For** each resource k_2 in $\mathbf{k}_2$ **do**
2.4	**For** each alternative resource k_4 in $\mathbf{k}_4$ **do**
2.5	**For** each batch of current product $b_2 = \overline{1, B_{l_3}}$ **do**
2.6	**For** each batch of alternative product $b_4 = \overline{1, B_{l_4}}$ **do**
2.7	**If** (precedence requirement element $\gamma(i_4, l_4, b_4, i_3 + m, l_3, b_2) = 0$ **and** ($i_3 \neq i_4$ **or** $\mathbf{k}_3 \neq \mathbf{k}_4$ **or** $l_3 \neq l_4$)) **then**
2.8	$\pi(i_1, k, \mathbf{k}_1, l_1, i_3 + m, k_2, \mathbf{k}_2, \mathbf{k}_3, l_3, b_2, i_4, k_4, \mathbf{k}_4, l_4, b_4) = st(i_1, k, \mathbf{k}_1, l_1, \mathbf{k}_2, i_3, \mathbf{k}_3, l_3)$
2.9	**Else** $(i_1, k, \mathbf{k}_1, l_1, i_3 + m, k_2, \mathbf{k}_2, \mathbf{k}_3, l_3, b_2, i_4, k_4, \mathbf{k}_4, l_4, b_4) = 0$

Figure 4.4 Step 2. Modelling SDM set-up operations versus processing operations

In Step 2 (Figure 4.4), we consider all the possible options for set-up versus processing operations, as defined by the set-up time requirement and the operational requirement sets, in relation with each other. This variation of the indices is performed in lines 2.1 to 2.4. The operations, resource subsets and products that need to be considered are thus identified. In the initialisation stage of $\pi\left(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4\right)$, the reference resource k and its previous state, the current operation, the sets of resources associated with the current and future operations, and the previous and current product are given by the variables of the set-up time element $st\left(i_1,k,\mathbf{k}_1,l_1,\mathbf{k}_2,i_3,\mathbf{k}_3,l_3\right)$, whereas the alternative operations will be given by $\phi\left(i_4,\mathbf{k}_4,l_4\right)$. The batch indices, b_2 and b_4 are calculated on the basis of the batch number for the reference set-up operation, B_{l_3} and the batch number corresponding to the alternative processing operation, B_{l_4} (lines 2.5 and 2.6). A π element will be initialised with a non-null value only for the elements that fulfil the following conditions (line 2.7):

- The processing operation i_4 for batch b_4 of l_4 should not precede the current set-up operation considered, $\left(i_3+m\right)$ for batch b_3 of product l_3 (therefore there is a sequence flexibility-related SDM option which needs to be modelled), **and**
- $i_3 \neq i_4$, i.e. the operation for which the reference resource is set-up is different than the alternative operation considered (therefore there is an operation flexibility-related SDM option which needs to be modelled) **or** $\mathbf{k}_3 \neq \mathbf{k}_4$, (i.e. there is a resource flexibility-related SDM option which needs to be modelled), **or** $l_3 \neq l_4$, i.e. the current product is different than the alternative product considered (therefore there is a product flexibility-related SDM option which needs to be modelled).

Similarly to Step 1, the fact that the term $b_2 \neq b_4$ is not included in the right term of the **If** condition (within the brackets with the **or** logical conditions) in line 2.7 models the fact that the set-up for a given operation on a given resource subset and a given product does not depend on the batch. Therefore, for the situation where ($\gamma(i_4, l_4, b_4, i_{3+m}, l_3, b_2) = 0$ **and** $i_3 = i_4$ **and** $\mathbf{k}_3 = \mathbf{k}_4$ **and** $l_3 = l_4$), no π element will be initialised for $b_2 \neq b_4$ for set-up operations versus processing operations. This models the fact that processing operation i_3 for reference resource k on resources $\mathbf{k}_3$ for product l_3 requires a set-up operation, therefore there is no option about it being run before the set-up.

The fact that the term $k_2 \neq k_4$ is not included in the right term of the **If** condition in line 2.7 models resource concurrency, that is the fact that all the resources k_2 in resource subset $\mathbf{k}_2$ have to be used simultaneously for set-up for the current operation, therefore they would not be available for other operations if the current operation is considered.

The elements that do not fulfil the conditions in line 2.7 will be set to 0 (line 2.9).

The state space visited by the conditions in line 2.7 consists of the combinations of any two options *set-up operation* versus *processing operation* for which no precedence relationship is defined. Two instances of these options are presented next:

1. For $i_3 = i_4$, investigate what are the alternative resource subsets $\mathbf{k}_4 \neq \mathbf{k}_3$ for operation i_3 for batch b_3 of product l_3.
2. For $\mathbf{k}_3 = \mathbf{k}_4$, investigate what are the alternative processing operations $i_3 \neq i_4$ that can be executed at this stage on this resource subset, either for alternative products $l_3 \neq l_4$, or for l_3-type products.

The value of a π element initialised in Step 2 is similar with the value in Step 1.

Step 3. Modelling SDM for processing operations versus processing operations

3.1 For each processing requirement element $\phi(i_2,\mathbf{k}_2,l_2) \neq 0$ **do**

3.2 **For** each alternative processing requirement element $\phi(i_4,\mathbf{k}_4,l_4) \neq 0$ **do**

3.3 **For** each reference resource k_2 in $\mathbf{k}_2$ **do**

3.4 **For** each alternative resource k_4 in $\mathbf{k}_4$ **do**

3.5 **For** each batch of current product $b_2 = \overline{1,B_{l_2}}$ **do**

3.6 **For** each batch of alternative product $b_4 = \overline{1,B_{l_4}}$ **do**

3.7 **If** (precedence requirement element $\gamma(i_4,l_4,b_4,i_2,l_2,b_2) = 0$ **and**
((operations $i_2 = i_4$ **and** resources $k_2 = k_4$ **and**
resource subsets $\mathbf{k}_2 = \mathbf{k}_4$ **and** products $l_2 = l_4$ **and** batches $b_2 = b_4$) **or**
(operations $i_2 \neq i_4$ **or** products $l_2 \neq l_4$ **or** batches $b_2 \neq b_4$))) **then**

3.8 $\pi(i_2,k_2,\mathbf{k}_2,l_2,i_2,k_2,\mathbf{k}_2,\mathbf{k}_2,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4) = \phi(i_2,\mathbf{k}_2,l_2) \times L_{i_2 l_2}$

3.9 **Else** $\pi(i_2,k_2,\mathbf{k}_2,l_2,i_2,k_2,\mathbf{k}_2,\mathbf{k}_2,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4) = 0$

Figure 4.5 Step 3. Modelling SDM processing operations versus processing operations

Step 3 of the algorithm (Figure 4.5) considers all possible options for processing, as defined by the operational requirement set, in relation with each other. This is done in lines 3.1 to 3.6. Then all the elements for which no precedence relation is defined, both diagonal and non-diagonal (defined by line 3.7) are initialised in line 3.8. The value that an element π takes represents the processing time required for processing operation i_2 for batch b_2 of product l_2 on resources $\mathbf{k}_2$, calculated as the product of the time of processing one product and its associated lot size, $L_{i_2 l_2}$ (line 3.8).

Specific to the $\pi(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4)$ elements that define the relationship *processing operation* versus *all the other operations* (initialised in Step 3 and Step

4), is the fact that Equation 4.6 holds true for their indices. The conditions in Equation 4.6 model the fact that the time required by processing operations does not depend on previous operations, and that for processing operations there is no enforced following operation or resource subset.

$i_1 = i_2$ **and** $k_1 = k_2$ **and** $\mathbf{k}_1 = \mathbf{k}_2 = \mathbf{k}_3$ **and** $l_1 = l_2$

Equation 4.6 The properties of the processing-related elements of the SDMC-contributing factor set

The **or** conditions in the **If** statement in line 3.7 define the alternative processing operations, for which any of the operation, product or batch index may differ from the current operation, product or batch index, respectively. When ($i_2 = i_4$ **and** $l_2 = l_4$ **and** $b_2 = b_4$), only the diagonal π elements will be initialised (line 3.7). The options $k_2 \neq k_4$ and/or $\mathbf{k}_2 \neq \mathbf{k}_4$ are not considered in this situation. This is due to the concurrency requirements (i.e. there is no option for running the same operation on all the resources in a resource subset), and to the fact that once an operation has been selected, the decision is focussed on the alternative operations and their corresponding resources and resource subsets, and not on the alternative resources on which it can be run. This is modelled through the fact that, for a given processing operation, no alternative option is considered for $k_2 \neq k_4$ and/or $\mathbf{k}_2 \neq \mathbf{k}_4$ when ($i_2 = i_4$ **and** $l_2 = l_4$ **and** $b_2 = b_4$) (line 3.7). This understanding is also explained by the fact that the decisions related to the resource and resource subsets on which to run an operation when several options are available is linked to the algorithmic complexity and scheduling optimization criteria, such as Shortest Processing Time, or The Least Utilised Resource [YP90].

Similarly to the previous steps, Step 4 (Figure 4.6) considers all possible options of *processing operations* versus *set-up operations*, in relation with each other (lines 4.1 to 4.6). Only the pairs (processing operation, set-up operation) for which no precedence relationships have been defined will result in their corresponding π element being set to a non-null value (line 4.8). Therefore, the algorithm models the fact that the SDMC-contributing factors for which the alternative operation is the set-up operation of the current processing operation will be set to 0. This is because, by definition, a set-up operation has to precede its corresponding processing operation (as defined by the extension of the precedence requirement set performed in Section 4.5.3.5 and 4.5.3.7). This statement is true even if the set-up operation is for a different resource subset than the current one, $\mathbf{k}_2$, as the operation has already become a current one.

The elements that do not fulfil the conditions in line 4.7 will be set to 0 (line 4.9).

Step 4. Modelling SDM for processing operations versus set-up operations

4.1 **For** each processing requirement element $\phi(i_2,\mathbf{k}_2,l_2) \neq 0$ **do**

4.2 **For** each alternative set-up time requirement element $st\left(i_1^*,k^*,\mathbf{k}_1^*,l_1^*,\mathbf{k}_2^*,i_3^*,\mathbf{k}_3^*,l_3^*\right) \neq 0$ **do**

4.3 **For** each current resource k_2 in $\mathbf{k}_2$ **do**

4.4 **For** each alternative resource $\mathbf{k}_3^*$ **do**

4.5 **For** each batch of current product $b_2 = \overline{1,B_{l_2}}$ **do**

4.6 **For** each batch of alternative product $b_4 = \overline{1,B_{l_3^*}}$ **do**

4.7 **If** $\gamma\left(i_{3+m}^*,l_3^*,b_4,i_2,l_2,b_2\right)=0$

4.8 $\pi\left(i_2,k_2,\mathbf{k}_2,l_2,i_2,k_2,\mathbf{k}_2,\mathbf{k}_2,l_2,b_2,i_3^*+m,k_4,\mathbf{k}_3^*,l_3^*,b_4\right)=\phi(i_2,\mathbf{k}_2,l_2)\times L_{i_2l_2}$

4.9 **Else** $\pi\left(i_2,k_2,\mathbf{k}_2,l_2,i_2,k_2,\mathbf{k}_2,\mathbf{k}_2,l_2,b_2,i_3^*+m,k_4,\mathbf{k}_3^*,l_3^*,b_4\right)=0$

Figure 4.6 Step 4. Modelling SDM processing operations versus set-up operations

The SDMC-contributing factor set defines the scheduling-related decision-making state space, obtained as a combination of diverse inter-related classes of flexibility, rather than based only on individual classes. The probability of observing a resource in a given state is computed by using the main diagonal elements of the SDMC-contributing factor set. The number and value of the non-diagonal elements represent a measure of the various classes of flexibility in the system.

The algorithms used in the definition of the SDMC-contributing factors ensure that no double initialisation occurs for processing operations. The interactions amongst products is modelled through the indices l_1, l_2 and l_4, and the interaction among batches through indices b_2 and b_4.

Based on the SDMC-contributing factor set we now define the normalized SDMC-contributing factors $\tilde{\pi}\left(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4\right)$ (Equation 4.7), in order to fulfil the definition of the entropy requirements (Section 2.7).

$$\tilde{\pi}\left(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4\right)=\frac{\pi\left(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4\right)}{\sum\pi\left(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4\right)}$$

Equation 4.7 The normalized SDMC-contributing factor

The elements $\tilde{\pi}\left(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4\right)$ thus satisfy the property of a probability set associated with a set of events, as required by the definition of the entropy (Section 2.7). However, it is worth emphasising that, due to the manner in which they have been calculated, these elements do not represent exact probabilities corresponding to basic events in the original system.

$$\sum\tilde{\pi}\left(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4\right)=1$$

Equation 4.8 The property of the normalized SDMC-contributing factors

The normalization of the SDMC-contributing factors converts the absolute processing or set-up times in relative processing requirements. This operation makes the results generic and comparable between different systems. The information-theoretic measure of SDMC is defined in the next section.

4.5.5 The scheduling-related decision-making complexity

The definitions and modelling performed so far in this chapter provide a sound foundation for the information-theoretic definition of the scheduling-related decision-making complexity. We use the entropy concept as introduced in information theory [Ash56, Sha48] to define SDMC as:

$$H_{SDMC} = -\sum_{\widetilde{\pi} \neq 0} \widetilde{\pi} \log_2 \widetilde{\pi} \text{, where } \widetilde{\pi} = \widetilde{\pi}\left(i_1, k, \mathbf{k}_1, l_1, i_2, k_2, \mathbf{k}_2, \mathbf{k}_3, l_2, b_2, i_4, k_4, \mathbf{k}_4, l_4, b_4\right)$$

Equation 4.9 The Scheduling-related Decision-Making Complexity

For a given schedule and schedule horizon, the variables that the SDMC depends on, and their meaning are presented in the previous section. The unit of measure of SDMC is bit.

Due to the manner in which the SDMC-contributing factor set has been generated, Equation 4.9 captures, integrates and quantifies valuable characteristics of the SDM process. The value provided by the formula in Equation 4.9 represents an upper bound of the SDMC, calculated on the basis of all the options available to the scheduler when making scheduling decisions for a given product set and demand, and a given system specification. Therefore, no information about what products have already been processed is available and could be used to reduce the amount of information that needs to be considered in the SDM phase. This understanding corroborates with, and further validates the conceptual definition of SDMC proposed in this thesis (Section 4.5.1).

The properties of the SDMC defined by Equation 4.9 are presented in Section 4.6.4. The next section extends the model of SDMC developed so far to systems with assembly and disassembly operations.

4.5.6 The computation of SDMC for systems with assembly/disassembly operations

In section 4.5.4 we proposed a method for modelling the SDMC-contributing factors of systems with single-input single-output operations. For the purpose of this thesis, we define an assembly operation as an operation with more than one input. A disassembly operation represents an operation with more than one output. Identical inputs or identical outputs of an operation will be referred to as homogeneous inputs and homogeneous outputs, respectively. Similarly, different inputs or different outputs of an operation will be referred to as heterogeneous inputs and heterogeneous outputs, respectively. An operation can therefore be both an assembly and a disassembly operation.

Additional modelling steps are required in order to assess the SDMC of systems with assembly and/or disassembly operations. This section describes how the SDMC of a system with assembly/disassembly operations can be assessed using the framework introduced so far in Section 4.5. To this aim, an algorithm for the conversion of a system with assembly/disassembly operations to a system with single-input and single-output operations is presented in this section.

When assembly/disassembly operations are required in the production stage, there are several new aspects that need to be considered and modelled alongside the features already considered so far:

1. The different types of raw materials;
2. The intermediate processing components (IPC) and the manner in which they have to be inter-linked in order to produce the final products of different types. An intermediate processing component represents a WIP product. The state of such a product needs to be appropriately defined so that it can be uniquely identified.
3. The production stages at which the IPCs are required for different products.

The assumptions made in order to address the SDMC of systems with assembly/disassembly operations are discussed next.

1. In practice, the raw material aspect is often addressed before the SDM stage. Therefore, the information on the different types of raw materials entering various operations is not included in the model. With this assumption, the raw material information would not bring additional SDMC, cost and value to the model of the analysed system.
2. An operation may generate more than one output, either intermediate processing component or final product.
3. An operation may require more than one input, either raw material or intermediate processing component.
4. The number and types of inputs and outputs of an operation does not depend on the resource and resource subset on which the operation is processed.
5. The number and types of outputs of an operation depends on the number and types of its inputs. However, a type of output is uniquely defined by the number and type of inputs, and by its associated operation (i.e. there is no flexibility associated with the inputs and operation-types required for a specific output).

As the characteristics presented in the above assumptions are typical for real manufacturing systems, these assumptions do not limit the applicability and the degree of generality of the method.

Proposition. A system with assembly and disassembly operations can be modelled as a system with single-input single-output operations by using a conversion algorithm comprising the following steps:

1. *System analysis.*
2. *Intermediate processing component definition.*
3. *Product decomposition/ redefinition.*
4. *Definition of the operational requirement specification.*

5. *The precedence requirement specification.*
6. *Calculation of the operation-specific lot sizes for the intermediate processing components.*

Once the conversion to a single-input single-output system has been performed, the algorithm in Sections 4.5.4 and 4.5.5 can be used to calculate the SDMC of the initial system. Each step of the conversion algorithm is presented in more detail below. We will also consider an example system for which we will explain what each step involves.

Step 1. System analysis

For a product set that has to be produced in a given schedule horizon, use the product definitions and requirement specifications in order to detect any product dependencies and the stages at which they occur (intermediate stages or final stages).

The example system considered is presented in Figure 4.7. There are two final products and four operations in the system, and the precedence relationships are $1\rightarrow2\rightarrow3\rightarrow4$ for product 1, and $1\rightarrow2\rightarrow3\rightarrow5$ for product 2. Operation 1 is a disassembly operation with homogeneous outputs, that generates inputs for both operation 2 and operation 3. Operation 2 is an assembly operation with homogeneous inputs. Two out the six outputs generated by operation 1 are used by operation 2, and the rest of four are used by operation 3. Operation 3 also uses an input generated by operation 2.

Operation 3 is an assembly/disassembly operation with heterogeneous inputs and outputs that generates outputs of type A for product 1 and outputs of type B for product 2. Operation 4 is an assembly operation with homogeneous inputs that generates product 1, and operation 5 is an assembly/disassembly operation with homogeneous inputs and outputs that generates product 2.

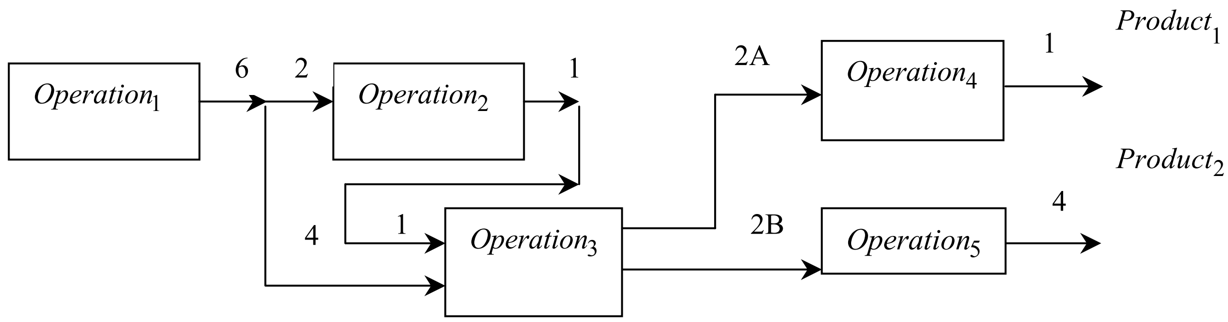

Figure 4.7 Example of a system with assembly/disassembly operations

Step 2. Intermediate component definition

For all operations of product l, if the type and number of outputs generated by an operational stage of product l *are not used entirely by an operation of any product*, define the overall output of that operation as an IPC. The order of definition of IPCs is imposed by the precedence constraints existing for the operations and products, starting from the earlier operations. This ensures that, once an IPC has been defined, all the related products that use an IPC-type intermediate product will be redefined to reflect this. An example is presented in Figure 4.8.

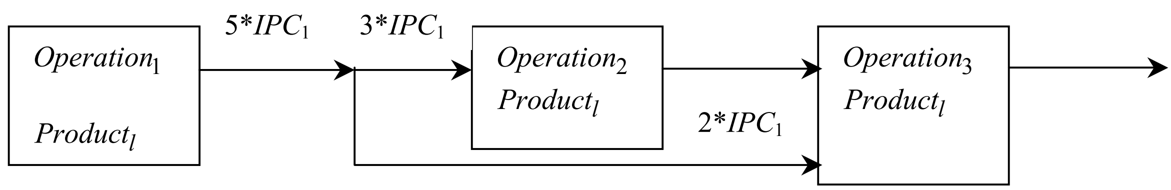

Figure 4.8 The Intermediate Processing Component definition

The situation in Figure 4.8 can be dealt with in two ways:

1. Operation 1 may be processed individually to produce the intermediate processing component for operation 2 ($3*IPC_1$) and operation 3 ($2*IPC_1$), respectively. This would minimize the WIP in the system, but might extend the lead times if non-null set-up times are involved. It would also add to the SDMC, as the operation would have to be scheduled twice.

2. Operation 1 may be run once for all the 5*IPC_1-type outputs required by operation 2 and operation 3 of product l. This would reduce the set-up times, the SDMC, and possibly the lead time, at the expense of increasing the volume of WIP in the system.

The method chosen by the Production Manager will determine the manner in which the lot sizes corresponding to each stage will be calculated. The relative SDMC of these strategies for complex assembly/disassembly systems can be assessed using the method presented in this section. What is important is that we can redefine the precedence relationships to model the fact that operation 1 for producing IPC_1 has to precede both operation 2 and operation 3. This modelling is also valid for the situation where operation 1 generates heterogeneous outputs. The impact of the introduction of IPC_1 on lot sizes is considered in Step 6 of the conversion algorithm.

Based on the IPCs defined by applying the algorithm presented at this stage, let us define a binary integer array, $\mathbf{IPC} = \left[IPC_1, IPC_2, ..., IPC_{u-n}, IPC_{u-n+1}, ..., IPC_u\right]$, with $u > n$ and n the total number of products. This array refers to both the intermediate processing components and the final products to be produced in a given schedule horizon. The indices $\overline{1,(u-n)}$ in **IPC** refer to the newly defined intermediate processing components, and the indices $\overline{(u-n+1),u}$ refer to the final products $Product_1, Product_2, ..., Product_n$.

According to the algorithm presented in this step, for the system in Figure 4.7, we define IPC_1 as the output of operation 1, IPC_2 as the output of operation 3, and product 1 and product 2 become IPC_3 and IPC_4, respectively. The **IPC** vector will have four elements, $\mathbf{IPC} = \left[IPC_1, IPC_2, IPC_3, IPC_4\right]$. These transformations are presented in Figure 4.9.

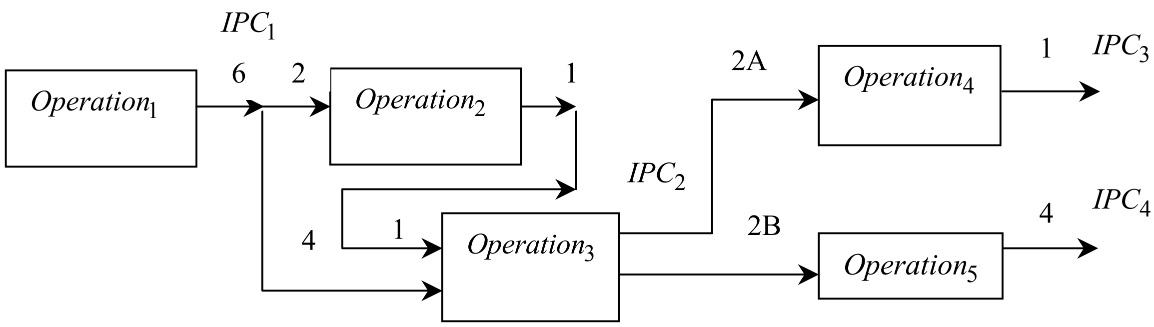

Figure 4.9 The definition of Intermediate Processing Components for the system in Figure 4.7

Step 3. Product decomposition/ redefinition

On the basis of Steps 1 and 2 above, redefine all the final product specifications in a new set of products that contains no operations of the type described in the IPC definition stage (Step 2). This is be done by introducing IPCs as inputs for an operational stage wherever necessary, according to the rule defined in Step 2.

For the system in Figure 4.9, the operations for each IPC are IPC_1 : operation 1; IPC_2 :operation2 and operation 3; IPC_3 : operation 4; IPC_4 : operation 5.

The redefinition of the products allows for product concurrency, i.e. several products being produced by a single operation, to be modelled.

Step 4. Definition of the operational requirement set

Based on the intermediate processing component definitions and on the final product definitions, define the operational requirement set (Table 4.1 and Section 4.5.3.4). i and $\mathbf{k}$ have the same meanings as defined in Section 4.5.3.4, i.e. $i = \overline{1,m}$ represents an index to the operations in the system, and $\mathbf{k}$ a resource subset on which operation i for IPC_l can be processed ($l = \overline{1,u}$ and $u > n$). Therefore, the total number of operations associated with a product set will remain constant, whereas the total number of products on which decisions have to be made increases. Notice that for all the operations that are common for several products, the resource requirements for all the products should be identical.

For the example system in Figure 4.7, the resource specifications for operations 1 to 3 should be identical for product 1 and product 2. In these conditions, assuming that there are two resources in the example system in Figure 4.7, and that:

- Operation 1 can be performed on resource 1, and operation 2 can be performed on resource 2, with processing time of one run being 10 and 20, respectively;
- Operation 3 can be performed on resource 2, in 30 time units;
- Operation 4 can be performed on resource 1, in 5 time units;
- Operation 5 can be performed on either resource 1 or resource 2, in 15 or 25 time units, respectively.

The operational requirement elements $\phi(i,\mathbf{k},l)$ for the **IPC** set has six non-null elements, as follows:

- Operation 1 for IPC_1 on resource 1: $\phi(1,\{1\},1)=10$
- Operation 2 for IPC_2 on resource 2: $\phi(2,\{2\},2)=20$
- Operation 3 for IPC_2 on resource 2: $\phi(3,\{2\},2)=30$
- Operation 4 for IPC_3 on resource 1: $\phi(4,\{1\},3)=5$
- Operation 5 for IPC_4 on resource 1: $\phi(5,\{1\},4)=15$ or resource 2: $\phi(5,\{2\},4)=25$

Step 5. The precedence requirement set

The precedence requirement elements $\gamma(i_1,l_1,b_1,i_2,l_2,b_2)$ (Table 4.1 and Section 4.5.3) can now be defined, with $i_1=\overline{1,m}$ and $i_2=\overline{1,m}$ operation indices, $l_1=\overline{1,u}$ and $l_2=\overline{1,u}$ IPC indices, and

$b_1 = \overline{1, B_{l_1}}$ and $b_2 = \overline{1, B_{l_2}}$ batch indices. B_{l_1} and B_{l_2} represent the number of batches of IPC_{l_1} and IPC_{l_2}, respectively, to be produced in a given schedule horizon. The information required at this stage consists of the initial precedence relationships between the operations of various final products, and of the definition of IPCs. n represents the total number of final products and $u - n$ the total number of IPCs components identified.

For the example in Figure 4.9, assuming that a single batch of each product has to be produced, then the following nine elements $\gamma(i_1, l_1, b_1, i_2, l_2, b_2)$ will be non-null:

- Operation 1 for IPC_1 precedes all the other operations for all the other IPCs: $\gamma(1,1,1,2,2,1) = 1$, $\gamma(1,1,1,3,2,1) = 1$, $\gamma(1,1,1,4,3,1) = 1$, $\gamma(1,1,1,5,4,1) = 1$
- Operation 2 for IPC_2 precedes all the other operations but operation 1: $\gamma(2,2,1,3,2,1) = 1$, $\gamma(2,2,1,4,3,1) = 1$, $\gamma(2,2,1,5,4,1) = 1$
- Operation 3 for IPC_2 precedes operation 4 and operation 5: $\gamma(3,2,1,4,3,1) = 1$, $\gamma(3,2,1,5,4,1) = 1$

By comparison, before introducing new IPCs, the number of precedence constraints was twelve, calculated from: 1→2→3→4 (three precedence requirements for operation 1, two for operation 2, and one for operation 4), and similarly for 1→2→3→5 for product 2. This is explained by the fact that, for overlapping operations, in the new configuration there would be a single precedence requirement initialised, whereas for the initial configuration there was one element for each product type.

Step 6. Computation of the operation-specific lot sizes for the intermediate processing components

The operation-specific lot sizes corresponding to all operations and intermediate processing components are calculated starting from the final stages towards the initial stages, by using one or several of the methods presented below.

The calculated lot size corresponding to an operation is defined as the number of times an operation should be run in order to achieve the required lot size for the final components (Table 4.1). By defining operation-specific lot sizes, no information on the number of outputs of a given product generated by a specific operation will need to be provided in the SDMC modelling and assessment stage. To calculate the new lot sizes of the final and intermediate components within systems with assembly/disassembly operations, we consider the fundamental cases, as presented below.

Calculation of the lot sizes of final products for homogeneous disassembly operations

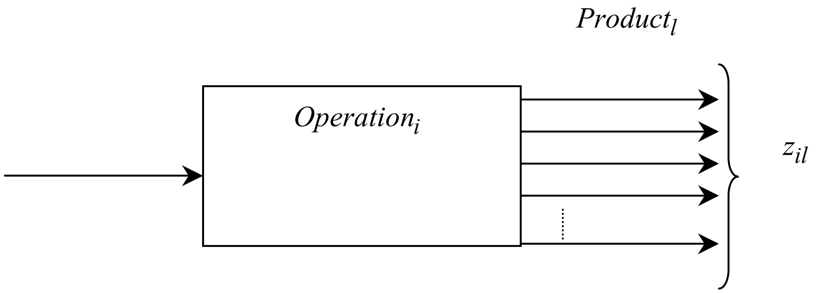

Figure 4.10 The lot sizes of final products for homogeneous disassembly operations

Assume that operation i generates z_{il} l-type final products (Figure 4.10) and that operation i is the final operation of product l. Then, the required number of products per batch for operation i is $q_{il} = \frac{Q_l}{B_l}$ (Table 4.1), and the lot size of product l for operation i, L_{il}, is given by:

$$L_{il} = \frac{q_{il}}{z_{il}} = \frac{Q_l}{B_l z_{il}}$$

Equation 4.10 The lot size for homogeneous disassembly final operations

Calculation of the lot sizes of final products for heterogeneous disassembly operations

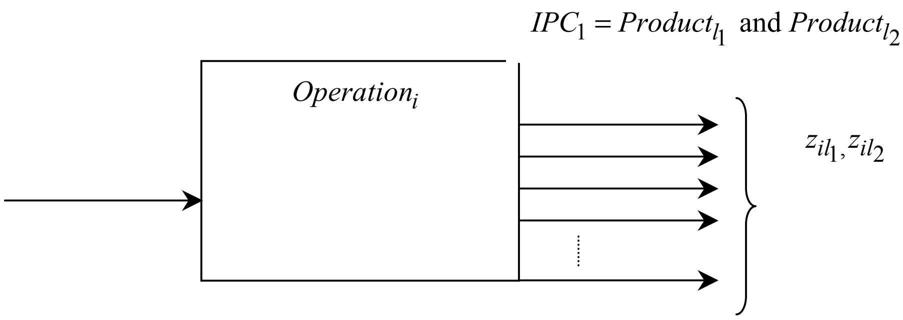

Figure 4.11 The lot sizes of final products for heterogeneous disassembly operations

If operation i generates z_{il_1} l_1-type final products and z_{il_2} l_2-type final products (Figure 4.11), the lot size L_{i1} corresponding to operation i for IPC_1 is given by Equation 4.11 below. This is explained by the fact that the maximum between L_{il_1} and L_{il_2} needs to be produced by operation i in order to accommodate the required number of both l_1 and l_2 products.

$$L_{i1} = \max\left(\frac{q_{il_1}}{z_{il_1}}, \frac{q_{il_2}}{z_{il_2}}\right) = \max\left(\frac{Q_{l_1}}{B_{l_1} z_{il_1}}, \frac{Q_{l_2}}{B_{l_2} z_{il_2}}\right)$$

Equation 4.11 The lot size for heterogeneous final disassembly operations

The optimal schedule would aim for $\frac{q_{il_1}}{z_{il_1}} = \frac{q_{il_2}}{z_{il_2}}$, condition which ensures the minimization of WIP or unused IPC. The formula in Equation 4.11 can be easily extended for heterogeneous disassembly operations with a generic number of types of outputs.

Calculation of the lot sizes of a two-layer one-to-one disassembly/ assembly operation

Let us now consider the case where operation i_1 generates $z_{i_1l_1}$ l_1-type IPCs, of which only $y_{i_2l_1} < z_{i_1l_1}$ are required for a single next operational stage, operation i_2, which has lot size $L_{i_2l_2}$ and generates l_2-type IPCs (Figure 4.12).

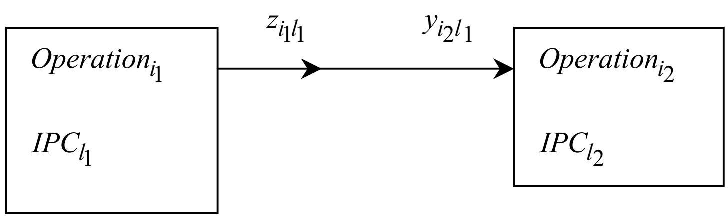

Figure 4.12 The lot size of a two-layer one-to-one disassembly/assembly operation

The lot size $L_{i_1l_1}$ corresponding to operation i_1 is calculated as a function of $z_{i_1l_1}$, $y_{i_2l_1}$ and $L_{i_2l_2}$ as described below.

We first impose the condition $z_{i_1l_1} \times L_{i_1l_1} \geq y_{i_2l_1} \times L_{i_2l_2}$, which models the fact that at least the number of inputs needed for a batch should be produced. Ideally, $z_{i_1l_1} \times L_{i_1l_1} = y_{i_2l_1} \times L_{i_2l_2}$, which models the fact that the exact number of inputs needed are produced by the precedent stage (this minimizes the WIP and reduces the WIP storage and handling costs, but it may be more costly due to the additional resource set-up and task scheduling costs). Equivalently, the latter condition becomes:

$$L_{i_1l_1} = \frac{y_{i_2l_1} L_{i_2l_2}}{z_{i_1l_1}}$$

Equation 4.12 The lot size for a two-layer one-to-one disassembly/assembly operation

Calculation of the lot size of a disassembly operation with homogeneous outputs used by several subsequent operations

Let us consider the case when:

- Operation i_1 generates $z_{i_1 l_1}$ l_1-type outputs;
- $y_{i_2 l_1}$ l_1-type inputs are required for operation i_2, which has lot size $L_{i_2 l_2}$ and generates l_2-type outputs,;
- $y_{i_3 l_1}$ l_1-type inputs are required for operation i_3, which has lot size $L_{i_3 l_3}$ and generates l_3-type outputs (Figure 4.13).

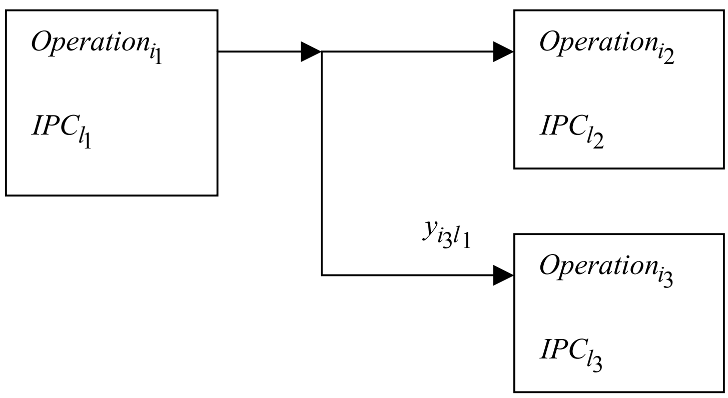

Figure 4.13 A disassembly operation with homogeneous outputs used by several subsequent operations

If operation i_1 is run individually/independently for each of the operations requiring the l_1-type component, the lot sizes are calculated as in the precedent case, with the following two lot sizes required:

$$L'_{i_1 l_1} = \frac{y_{i_2 l_1} L_{i_2 l_2}}{z_{i_1 l_1}}$$ for operation i_2, and

$$L''_{i_1 l_1} = \frac{y_{i_3 l_3} L_{i_3 l_3}}{z_{i_1 l_1}}$$ for operation i_3

If operation i_1 is run jointly for both operations requiring it, then:

$$L_{i_1 l_1} = L'_{i_1 l_1} + L''_{i_1 l_1} = \frac{y_{i_2 l_1} L_{i_2 l_2} + y_{i_3 l_1} L_{i_3 l_3}}{z_{i_1 l_1}}$$

In general, for $o \geq 1$ operational stages following a given homogeneous disassembly stage i of product l, L_{il} would be given by:

$$L_{il} = \frac{\sum_{j=1}^{o} y_{i_j l_1} L_{i_j l_j}}{z_{i_1 l_1}}$$

Equation 4.13 The lot size of a disassembly operation with homogeneous outputs used by several operations

The operation-specific lot sizes for the example in Figure 4.7 are calculated next, assuming that 10 products 1 and 16 products 2 need to be produced, each of them in a single batch.

1. The lot size for operation 4 and IPC_3, calculated using the formula in Equation 4.10, is:

   $$L_{43} = \frac{10}{1} = 10$$

2. The lot size for operation 5 and IPC_4 is also calculated using the formula in Equation 4.10:

   $$L_{54} = \frac{16}{4} = 4$$

3. The lot size for operation 3 for IPC_2 is calculated using a combinations of the formulae in Equation 4.11 and Equation 4.12:

   $$L_{32} = \max\left(\frac{L_{43} \times 2}{4}, \frac{L_{54} \times 2}{2}\right) = \max\left(\frac{10 \times 2}{4}, \frac{4 \times 2}{2}\right) = 5$$

4. The lot size for operation 2 for IPC_2 is calculated using the formulae in Equation 4.10 and Equation 4.12:

   $$L_{22} = \frac{5 \times 1}{1} = 5$$

5. The lot size for operation 1 for IPC_1 is calculated using the formula in Equation 4.13:

$$L_{11} = \frac{L_{22} \times 2 + L_{32} \times 4}{6} = \frac{5 \times 2 + 5 \times 4}{6} = 5\,.$$

At this stage, all the information required for the initialisation of the SDMC-contributing factors as defined in Table 4.1 is available, so the proof of the proposition that a system with assembly/disassembly operations may be converted into a single-input single-output system is complete.

Remarks

1. The new lot sizes corresponding to the operations should be calculated from the final processing stages towards the initial processing stages.
2. In practice any lot size L should be greater or equal than 1, although this condition may imply sometimes that more intermediate components than required will be produced in a single production run.
3. When an output is distributed to several operational stages, and operations are run independently for each of them, more scheduling decisions have to be made in order to reschedule the operational stage to produce all the components. The alternative of jointly producing all the IPCs required for several subsequent stages involves more WIP in the system.

This section has proved that, for SDMC calculation purposes, a system with assembly and disassembly operations can be transformed into a system with single-input single-output operations. The SDMC modelling and calculation method presented in Sections 4.5.4 and 4.5.5 can now be applied to the newly obtained system. An important remark is that the new system with single-input single-output operations has the same number of operations as the original system. The number of products will increase due to the introduction of IPCs. The number of precedence relationships will decrease, as for overlapping operations there would be a single precedence requirement element initialised, whereas before there was one element for each product type. The next section will discuss applicability and methodological issues related to the SDMC measure.

4.5.7 Scheduling-related decision-making complexity: Utility, meaning and methodological issues

This section discusses practical issues related to the SDMC measurement framework:

1. *Application domain.* SDMC (Equation 4.9) has to be calculated for all the resources used by a given product set in a given scheduling horizon, in order to assess the level of interaction among the product requirements and resources.
2. *Calculation of off- and on-line SDMC*. When there is only off-line scheduling-related decision-making, the total SDMC value is obtained by applying the SDMC calculation method on the planned product set for the given system specification. For on-line SDM, the SDMC calculation method has to be applied every time a scheduling decision is made. The total SDMC value will reflect the fact that some of the products or batches have been re-scheduled once or several times.
3. *Analysis interval*. The period for which SDMC is calculated is determined by:
   - The problem to be investigated;
   - The time for which reliable and to the required level of detail operational data is available. A typical and representative system behaviour should ideally be aimed for.
4. *Level of detail.* The level of detail of the modelling should be system- and product set-specific. For example, for single batch product sets, the indices b_2 and b_4 will always be 1, and will therefore not bring any new information in the SDMC framework. Similarly, if there are no sequence-specific set-up operations, all the operations will be modelled as processing operations, and the indices i_1, $\mathbf{k}_1$, l_1, k_2, $\mathbf{k}_2$ in the SDMC-contributing factors will not bring any new information to the model, so they can be ignored. The processing requirement set and the precedence requirement set will have to capture this by including the set-up

operations as additional processing operations. Furthermore, the set-up and set-up time requirement sets will be empty, so the precedence requirement set will not need to be extended to include the precedence relationships between set-up operations and processing operations. This situation is captured automatically by the modelling framework.

5. *Utility and meaning*. The scheduling-related decision-making complexity assessment process provides an objective measure of the SDMC associated with a given product set and scheduling horizon, as well as with the individual contributions of various classes of entities (and therefore flexibility) to the total SDMC.
6. *Result interpretation and analysis*. Possible comparisons and analyses based on the scheduling-related decision-making complexity include:
   - Temporal-based comparisons between the SDMC of the facility for equivalent time periods, in order to identify and assess system changes at different moments in time.
   - Comparisons of the structure of the SDMC values for different time intervals relevant for the organisation.
   - Comparisons of SDMC values corresponding to operation, product and resource levels, or to combinations of any two of these levels, in order to identify the highest areas of demand and flexibility.
   - Investigation of the relationship between SDMC, SC and OC.
   - Investigation of the relationship between SDMC and specific target values of classical performance measures, such as expected machine utilization, average lead time and customer satisfaction.

One of the strengths of the SDMC measurement framework is to integrate and quantify different aspects of SDMC in manufacturing. It therefore provides a sound basis for comparing the SDMC levels of different facilities, or those corresponding to different time periods within a given facility. Hence, the SDMC values provided by this method can be used as a performance measure with predictive capabilities. Furthermore, SDMC can act as a bridge between the scheduling and production performance levels, as well as between the analytic (quantitative) and synthetic (qualitative) perceptions of the scheduling-related decision-making complexity. The SDMC measurement method answers a question of major importance for manufacturing, i.e. what is the volume and structure of information that have to be processed in order to create a schedule that satisfies a given set of constraints. Therefore, this technique is applicable to any environment where decisions have to be made. Practical applications of the SDMC measurement methodology to different manufacturing layouts and scenarios will be presented in Chapter 5.

If a set-up operation has to be performed always before its processing operation, and the set-up time does not depend on the previous operation, then for modelling purposes it becomes a processing operation, and it should be modelled accordingly in the operational and precedence requirement sets and SDMC factor set. This approach conforms to the manner in which scheduling-related decision-making would be performed in such a case, i.e. the scheduler would not consider the previous operation on a resource.

This section has provided answers to fundamental issues related to the conceptual and analytical definition of scheduling-related decision-making complexity. The next section investigates individual and inter-related capabilities of the complexity classes defined in this chapter.

4.6 System design, performance prediction and control capabilities of the complexity measures

Several fundamental properties of the structural, operational and scheduling-related decision-making complexity will be presented and discussed in this section, with direct applicability to manufacturing systems. The properties of the complexity measures derived from the intrinsic properties of entropy are presented in Section 4.6.1. Additional properties derived from applying the measures within the manufacturing context are also presented and discussed.

4.6.1 Capabilities of complexity measures derived from the properties of the entropy

The interpretation of the unique properties of the entropy for SC, OC and SDMC is performed below.

CP1. The value of the complexity of a system with two or more states (for SC and OC), or states and SDM options (for SDMC) is higher than the value obtained for a single-state or single option system. (This property is derived from axiom EA1 in Section 2.7).

CP2. For equally likely states or options, the measured value of the SC, OC and SDMC increases with an increase in the number of states or SDM options. (This property is derived from axiom EA2, Section 2.7).

CP3. For a given system configuration, the highest value of SC, OC and SDMC is obtained for equally likely states or SDM options. (This property is derived from axiom EA3, Section 2.7).

CP4. The value of the SC, OC and SDMC does not increase if a new state or option that does not appear in the current configuration is added to the system. (This is explained by the fact that the probability associated with the respective state or option is null, and it therefore does not contribute to the total SC, OC or SDMC (axiom EA4, Section 2.7)).

CP5. If the original product mix is split in two or more sets grouped according to a criterion such as operations, resources or products, then the overall SC, OC and SDMC can be calculated as a function of each set's individual SC, OC and SDMC. (This property is derived from axiom EA5, Section 2.7).

4.6.2 The properties of structural complexity

Structural complexity can usually be reduced more effectively by removing a resource rather than by removing a product [CES+00, Fri98, FS01]. The explanation for this property is the fact that SC is reduced linearly in the former case, and logarithmically in the second (Equation 4.2). This property provides a priority criterion for the structural complexity aspects to be embedded in the system in the design stage.

4.6.3 The properties of operational complexity

In the operational stage, a comprehensive specification of the system includes observing the dynamics of the queueing behaviour corresponding to each resource, as well as the states at each resource.

For Markovian queues at single-node systems, Frizelle and Suhov analytically proved that, if state j means that there are j items in the queue, and OC is calculated on the basis of this state definition, *OC increases as the system approaches its capacity* [FS01, Kle75]. Therefore, for this class of systems, the higher the OC, the longer products take to pass through the system. Furthermore, with increasing OC levels, the level of predictability decreases. This property is confirmed by the practice of manufacturing systems. Therefore, OC represents a valuable and valid means to integrate and quantify operational aspects of manufacturing. The absolute value of OC, as well as its structure, provides objective and informed indications for directions of control and long-term improvement.

Furthermore, Frizelle and Suhov proved that for Markovian queueing networks, the busiest resource has the highest OC, and therefore is the bottleneck of the process [FS01]. The busyness coefficient is determined as the ratio between the total arrival rate at the resource in equilibrium and the mean service time of that resource. Therefore, OC represents a method of identifying the bottlenecks, and assessing their criticality. The increased value of the OC resides in the fact that it allows the detection of volatile bottlenecks and, by investigating the structure of the OC and the recorded reasons, the identification of cause-effect relationships, such as persistent resource breakdowns, frequent and long resource changeovers, and critical products or customers.

4.6.4 The properties of scheduling-related decision-making complexity

The properties of SDMC will be discussed in more detail in this section. The SDMC measure defined in Section 4.5 quantifies the volume and structure of the information considered when making scheduling decisions for a given system and product set.

Definition 4.5 Within the SDMC framework, a processing or set-up time t_1 associated with a new entity to be added to the product set is said to be time-comparable with the existing operations if there exists a processing or set-up operation whose time t_2 satisfies:

$$\frac{t_2}{t_1} \le \varepsilon, \varepsilon = 0.5$$

Equation 4.14 The time-comparability definition

By processing time in Definition 4.5 we mean the operation processing time per product multiplied by its corresponding lot size. The new entity could be a new processing or set-up operation, or an additional option for running an operation on an existing or new resource.

SDMC has the following important properties:

SDMCP1. For comparable operation times, SDMC increases with an increase in product flexibility, i.e. with the number of types of products scheduled on a given system configuration. An increase in the number of products in the product set will determine an increase in the number of non-null elements of the SDMC-contributing factor set, through the indices l_1, l_2 and l_4.

SDMCP2. For comparable operation times, SDMC increases with an increase in operation flexibility or resource sharing, i.e. with the number of resources that can process a given operation set. An increase in the number of resources that can process a given product set will determine an increase in the number of non-null elements of the SDMC-contributing factor set, through the indices k, k_2, k_3 and k_4.

SDMCP3. For comparable operation times, SDMC increases with an increase in resource flexibility, i.e. with an increase in the number of operations that can be processed by a given resource set. An increase in the number of operations that can be processed by a given resource set for a given product set will determine an increase in the number of non-null elements of the SDMC-contributing factor set, through the indices i_1, i_2 and i_4.

SDMCP4. For comparable operation times, SDMC increases with an increase in resource concurrency. An increase in the level of concurrency will determine an increase in the number of non-null elements of the SDMC-contributing factor set, through the indices $\mathbf{k}_1$, $\mathbf{k}_2$, $\mathbf{k}_3$ and $\mathbf{k}_4$.

SDMCP5. SDMC increases with an increase in sequence flexibility, i.e. with a reduction in the number of precedence constraints for the products in the product array. An increase in the level of concurrency will determine an increase in the number of non-null elements of the SDMC-contributing factor set, through the indices i_4, k_4, $\mathbf{k}_4$ and l_4.

SDMCP6. SDMC increases as the lot size decreases, as more decisions need to be taken (lot flexibility). An increase in the total number of batches to be scheduled and produced, due to a decrease in the lot size, will determine an increase in the number of non-null elements of the SDMC-contributing factor set, through the indices b_2 and b_4.

SDMCP7. For comparable set-up times, SDMC increases if there are sequence dependent set-ups in the system. The introduction of sequence dependent set-ups will determine an increase in the number of non-null elements of the SDMC-contributing factor set, through the indices i_1, $\mathbf{k}_1$ and l_1.

SDMCP8. For the same level of resource, operation, precedence and lot flexibility, SDMC will depend on the processing and set-up times required by the operations on specific resources (set-up and processing time flexibility).

SDMCP9. If all the elements of the SDMC-contributing factor set are equal, then SDMC is a monotonically increasing function of the number of products in the product set.

SDMCP10. If all the elements of the SDMC-contributing factor set are equal, then SDMC is a monotonically increasing function of the number of resources in the resource set.

SDMCP11. If all the elements of the SDMC-contributing factor set are equal, then SDMC is a monotonically increasing function of the total number of operations associated with the product set.

SDMCP12. If all the processing times are equal for the products in the product set, then SDMC will increase because more SDMC-contributing factors will have equal values. (If all the lot processing sizes and set-up times are equal, then all the SDMC-contributing factors will have the same value).

SDMCP13. SDMC increases with an increase in the similarity of products, up to a point where they are no longer distinguishable in separate products, beyond which SDMC decreases since the number of products in the system decreases (products with the same processing, set-up and precedence requirements are considered as one product type).

SDMCP14. For a given product set, all other operating conditions remaining constant and the system working under an optimal control policy (i.e. correct scheduling decisions are made at each decision stage), the average waiting time and average lead time decrease with an increase in SDMC. The proof for this property is based on the fact that, for a given product set, higher SDMC values correspond to either increased levels of resource flexibility, increase in the number of resources, or higher sequence flexibility. This corresponds to higher probabilities for a resource to be available for at least one given task than in the initial configuration, and therefore to lower or equal probabilities of a task waiting for a resource. Furthermore, if the operating conditions remain constant, then the average lead time (calculated as the sum of the average waiting time and the average processing time), also decreases with an increase in SDMC. This proof is similar to the proofs given by Benjaafar and Deshmukh *et al.* [Ben92, Des93, DTB98].

The time comparability condition in properties SDMCP1-SDMCP4 and SDMCP7 above ensures that the re-evaluation of the values that the elements of the SDMC factor set take due to the addition of the new entity, plus the contribution of the new elements, will determine an increase in the SDMC. When the time comparability condition (Equation 4.14) is not fulfilled, SDMC will either increase or decrease, depending on the new relationships among the elements of the SDMC-contributing factor set. For example, when the newly added entity would require a much longer time than any existing operation, the SDMC will decrease. This is explained, analytically, by the change of scale when calculating SDMC by using the formula in Equation 4.9. Due to the introduction of a new element significantly higher than the others, the $\tilde{\pi}\left(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4\right)$ element corresponding to all the other operations in the system will now change and approach 0. This means that the previous operations in the system will contribute with smaller amounts to the total SDMC index than before the introduction of the new operation. Qualitatively, this corresponds to a shift in priorities in the scheduling-related decision-making process, which happens every time one or several jobs take significantly more time than the others do. This property will be exemplified and discussed in more detail in Section 5.1.9.

The value $\varepsilon = 0.5$ used in the time-comparability condition has been obtained experimentally and ensures that the properties SDMCP1-SDMCP4 and SDMCP7 are true. However, the exact values of ε for which these properties hold true are dependent on the type of entity added, and on the values that the current elements of the SDMC factor set take.

The SDMC of a product set can be calculated as the sum of the complexity of its subsets only when its subsets are independent, that is:

- There is no resource sharing among products;
- There are no precedence relationships between products;

- There are no assembly/ disassembly operations that require intermediate processing components.

Only in this situation, the scheduling is performed independently for each set of independent products.

The SDMC formula (Equation 4.9) represents the only function satisfying all the above properties (i.e. SDMCP1-SDMC14). The proof of this statement is based on the proof of the statement that the basic entropy formula defined by Shannon [Sha48] satisfies the axioms EA1 to EA4 presented in Section 2.7, as proved in [Sha48] and [Ash65]. Since the $\widetilde{\pi}$ elements satisfy Equation 4.8, the higher dimensionality of the SDMC measure defined in Section 4.5.5, Equation 4.9 can be transformed in a single sum by re-indexing, and it therefore does not affect the fundamental nature of the entropy as defined by Shannon. This reasoning is similar with the proof performed by Deshmukh [Des93].

This section has presented several important properties of the SDMC measure. The next section will further develop on the practical properties and applications of the complexity measures and on their joint value.

4.6.5 Joint structural, operational and scheduling-related decision-making properties and analyses

The complexity classes defined in this chapter have individual value and applicability. They also have joint meaning and can be analysed in relationship with each other to provide meaningful quantitative and qualitative insights on the investigated system. Several such properties and possible types of analyses are discussed in this section.

For a given system, the SDMC complexity is higher than or equal to SC. This property is derived from the fact that SC (Equation 4.2) is a simplified version of the SDMC measure given by

Equation 4.9. One explanation of this fact comes from the conceptual definitions of SDMC and SC. Furthermore, the information on the routing, product and process flexibility has been considered and dealt with in the SDM phase, and therefore structural complexity contains no information on the sequence of jobs. Once a feasible schedule has been created, the structure and volume of the information to be considered at the production stage is only that in the schedule. Analytically, this is represented by the probability of a resource being in a specific state, for all the resources in the system. The volume and structure of this information are quantified by Equation 4.2.

For SC and OC, coarser state definitions will yield lower complexity values. Merging some of the states in the system in macro-states (a process that Frizelle & Suhov [FS01] termed as categorization) will yield lower complexity values.

There is no predefined relationship between SC and OC. Insight in the meaning of their actual values can be obtained by looking at their structure and at the reasons for differences between them.

Visibility and Hierarchical Decomposition. The analysis of the structure of the SC, OC and SDMC values may be performed at the required level of detail. Resource-, operation-, product-, and interface-based analyses may be performed for all the three measures. Furthermore, a reason-based analysis may be performed for OC. This allows traceability and assessment of cause-effect relationships related to deviations from the expected behaviour in the operational stage.

Practical meaning and insight. A complexity index, H represents the amount of information required to define the state of the system in a specific dimension, SC, OC or SDMC. A degree of variety of 2^H corresponds to a complexity of H. The absolute value H in itself does not provide sufficient relevant information on the system. Useful insights may be obtained by comparing complexity values corresponding to a system for different periods of time of identical duration, or for different facilities. When the complexity value is correlated with measures of cost and value, sound decisions based on complexity, cost and value may be taken ([EC02] and Section 7.2.1).

Several categories of complexity-based investigations that could be performed on a manufacturing system, and their potential benefits are presented in Table 4.3. Due to their capabilities and the insights they can provide, structural and decision-making complexity analyses can be performed either in the process or product design stages, or in the production stage. Operational complexity analysis can only be performed in the operational stage, and its results provide insights into better control, management and design.

Table 4.3 Additional types of joint complexity analyses

No.	Type of Analysis	Issue investigated and assessed	Applicability/Benefit
1.	Calculate SC and SDMC for different system designs such as home-line or Group Technology strategies	The relationships between product and system structure, and SC and SDMC values	Apply in the design or re-design stage as a support tool for decision-making design
2.	Calculate SC, SDMC and OC for historical data	The long-term assessment of structural and operational parameters	Identify recurrent long-term problems, such as unfeasible schedules, faulty resources, quality problems
3.	Calculate the costs of materials, labour and resources, versus their added-value, and compare with corresponding complexity values	The trade-off between the cost and the added-value of running and controlling the production	Identify and quantify critical entities, products, labour or resources, such as low value-adding products with high production and control costs, and possibly consider outsourcing or other methods to increase efficiency and added value

4.	Calculate the SC and OC of the planning and scheduling documents	The structure and dynamics of scheduling documents, and cause-effect relationships related to the scheduling process	Assess the value of transmitting information, and the extent of customer changes or inaccurate information
5.	Analyse the structure of OC and the reasons for deviations from the expected behaviour	Strategic issues such as misaligned or misinterpreted performance measures, unreliable resources, and their impact on the actual system behaviour	Identify and assess intricate relationships, from which to derive critical directions for improvement
6.	Calculate the SC and OC at the intra- or inter-company interfaces, for both material and information flow	Poor quality of information or material (captured through quantity variations), or delayed or poorly synchronised information or material items (through time variations)	Objective measure of inter- and intra-organisational issues, such as poor customer satisfaction
7.	Calculate the combined SC and OC of resources and their associated queues.	Heavily loaded resources are potential bottlenecks. In the operational stage, highly volatile queues identify the bottlenecks.	Identify and assess criticality of bottlenecks, and possibly relate this to specific products

4.7 Summary

The information-theoretic, time-, process- and control- based complexity framework presented in this chapter represents a valid and generic approach to the systemic and integrated understanding, design and management of manufacturing systems. The proposed complexity metrics have the ability to integrate the material and information flows when identifying, quantifying and addressing the problems. The aspects measured emerged from the understanding that complexity is not only costly, but–when properly managed– it is also value-adding. The proposed measures possess valuable capabilities such as meaningfulness, comparability and predictability, and practicality. They can be applied to any class of manufacturing system, and even more, to any state-based system, in order to detect and assess problems, and identify directions for improvement.

The development of the manufacturing complexity framework has been performed through many iterations and refinements, using the knowledge and experience gained through a significant number of case studies, simulations and analytical modelling. There are numerous classes of applicability of the framework, several of which have been listed in Section 4.6.5.

The types of issues which a complexity-oriented analysis can detect and assess include: obstacles to specific activities (such as planning, scheduling, production), unplanned events and their impact on the overall activity, the quality and timeliness of the information used, or the validity and realism of the plan/schedule. Another important point is that the complexity classes defined in this chapter overlap and are inter-dependent. Different classes of complexity can be assessed individually or in relationship with each other, but due to the high degree of connectivity between them, a measure that would link all of them and give a global manufacturing measure has so far not been defined. This means that global complexity-based comparisons between manufacturing facilities cannot be performed based on the framework presented in this thesis. However, specific comparisons between manufacturing environments can be performed, either at a specific complexity class level, or in terms of combinations of classes of complexity.

The level of detail in defining specific tasks which impact upon manufacturing complexity is related to the specific issue investigated. Furthermore, the given period for which the time- and control-based complexity classes are investigated depends on the volume and quality of historical information available, and on the costs of performing measurements. Even short-term investigations can detect and assess persistent issues within a manufacturing company. These aspects are discussed in more detail in Chapter 6. The result comparability issue and its relationship to the state definition are considered in more detail in [SECH01b, Siv01]. The application of the manufacturing complexity framework creates an awareness of the problems existing within the organisation. Even in the early stages of its application, the method could detect crucial issues within the analysed facility.

Particular examples of calculating various classes of complexity are presented in Chapter 5. A methodology for measuring complexity and its application in a case study are presented in Chapter 6.

5 Computation and Interpretation of Complexity

All the books in the world contain no more information than is broadcast as video in a single large American city in a single year. Not all bits have equal value.
Carl Sagan [Sag]

The purpose of this chapter is to illustrate how various classes of complexity are calculated and interpreted, i.e. how the manufacturing complexity framework presented in Chapter 4 addresses the research questions 3 to 9 in Section 1.2. This is performed in two stages. First, in Section 5.1 several simple examples are considered and the manner in which the scheduling-related decision-making complexity is modelled and calculated for each of them is presented (Table 5.1).

Table 5.1 Summary of examples

Example	Section
The reference system (Two resources, One product, Two operations)	5.1.1
The effect of the number of operations and resource sharing on SDMC (Two resources, One product, Four operations)	5.1.2
The effect of the number of resources on SDMC (Four resources, One product, Two operations and Four resources, One product, Four operations)	5.1.3 (5.1.3.1 and 5.1.3.2)
The effect of resource concurrency on SDMC	5.1.4
The effect of the number of products on SDMC	5.1.5
The effect of operation precedence on SDMC	5.1.6
The effect of lot sizes on SDMC	5.1.7
The effect of sequence-dependent set-up operations on SDMC	5.1.8
The effect of “famous by duration” operations	5.1.9

New dimensions of SDMC are introduced with each new example, and their effects on the value that the SDMC takes and on its components are assessed and explained. The manner in which each component in the SDMC framework proposed in Section 4.5 is defined and used is thus illustrated for various system configurations. The examples considered in Section 5.1 are presented in Table 5.1.

Next, in Section 5.2 the scheduling-related decision-making, structural and operational complexity values are calculated for a devised multi-operation, multi-resource and multi-product system. These values are then interpreted in a useful manner, with an emphasis on their integrative capabilities. In order to further illustrate the applicability and usefulness of the methodology presented in Chapter 4, the kanban system considered in Chapter 3 is analysed from an information-theoretic perspective in Section 5.3. The SDMC results presented in this chapter were generated using a computer tool written in the C programming language on the basis of the methodology presented in Section 4.5. A brief description of the tool was presented in [ECB01, ECB02]. Due to space constraints, the source code for the tool is not included in the thesis.

5.1 Computation and Interpretation of Scheduling-related Decision-Making Complexity

5.1.1 The reference system (Two resources, One product, Two operations)

In this section we will consider a simple system with two resources (r=2) performing two operations (m=2) of a single type of product (n=1). For this system we will explain how the SDMC is calculated. Then, in the following sections of this chapter, we will use this example as the basis for introducing new features and assessing their effects on SDMC.

The definitions of these operations and resources for the reference system are presented in Table 5.2. Ten products have to be produced in one batch, therefore $Q_1 = q_1 = L_1 = 10$.

Table 5.2 Operational and processing time requirements for the reference system (Two resources, One product, Two operations)

Product ($l = \overline{1,n}$)	Operation ($i = \overline{1,m}$)	Resource k	Resource subset $\mathbf{k}$	$(i,\mathbf{k},l)$	$\phi(i,\mathbf{k},l)$
1	1	1	$\{1\}$	$(1,\{1\},1)$	10
	1	2	$\{2\}$	$(1,\{2\},1)$	20
	2	1	$\{1\}$	$(2,\{1\},1)$	10
	2	2	$\{2\}$	$(2,\{2\},1)$	30

As shown in Table 5.2, the two resources are flexible: operation 1 and operation 2 can be run on either of them, with different processing times. The operational requirement set has four elements, as illustrated in Table 5.2. These elements uniquely specify the resource and operation flexibilities, and the requirements associated with product 1. No resource concurrency is present in this system. Running any of the operations requires only one resource. This is modelled by each resource subset containing just one resource, as shown in Table 5.2. Also, no set-up operations and no precedence constraints are present in the system, therefore the precedence, set-up and set-up time requirement sets are all null.

The SDMC-contributing factor set will be initialised using only Step 3 of the algorithm defined in Section 4.5.4 (Figure 4.5), corresponding to processing operations versus processing operations SDM. The indices of the SDMC-contributing factors and their corresponding values are presented in Table 5.3.

As a reminder, for each SDMC-contributing factor $\pi(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4)$ the indices i_1, $\mathbf{k}_1$ and l_1 refer to the previous task on the reference resource k. Indices i_2, k_2, $\mathbf{k}_2$, l_2 and b_2 refer to the current task on the reference resource k. The $\mathbf{k}_3$ is only relevant when the current operation is a set-up operation, and defines the resource subset the reference resource will belong to during the processing operation for which it is currently being set. When the current operation is a processing operation, then $k = k_2$ and $\mathbf{k}_1 = \mathbf{k}_2 = \mathbf{k}_3$. The indices i_4, k_4, $\mathbf{k}_4$, l_4 and b_4 represent the alternative tasks that the decision maker has to consider when making a scheduling decision about the current task, as defined in Section 4.5.4. The number of non-null non-diagonal elements of the SDMC-contributing factor set represents the number of decisions that have to be made according to what operation to run next, and on which resource.

As there are no sequence-dependent operations in the system, the information on the previous operation does not need to be included in the modelling. Therefore, $i_1 = i_2$, $l_1 = l_2$, $k = k_2$ and $\mathbf{k}_2 = \mathbf{k}_3$ for all the non-null elements of the SDMC-contributing factor set. From the fact that no operations require more than one resource, we have the additional properties that $\mathbf{k}_2 = \{k_2\}$ and $\mathbf{k}_4 = \{k_4\}$ for all the possible scheduling-related decisions. Additional reductions in the complexity of the SDM task are due to having just one type of product and just one batch to schedule. These characteristics are represented by the conditions $l_2 = l_4 = 1$ and $b_2 = b_4 = 1$. Therefore, we can eliminate indices i_1, l_1, k, $\mathbf{k}_2$, $\mathbf{k}_3$, l_2, b_2, $\mathbf{k}_4$, l_4, and b_4 from the modelling, as they do not bring any additional information (Table 5.3). The reduced number of indices required for the modelling of SDMC for the system in this example demonstrates the flexibility of the SDMC measurement framework. This example also illustrates the reduction in the dimensionality of the problem for this particular system.

Since there are no precedence constraints between operations, the SDMC will integrate and quantify the potential sequence flexibility allowed by the combination operation-resource flexibility, as well as the various processing times associated with each operation. Therefore, the only indices that carry information, and therefore are relevant to the modelling for this example are i_2, k_2, i_4 and k_4, and the value that their corresponding SDMC-contributing factor:

$$\pi\left(i_1,k,\mathbf{k}_1,l_1,i_2,k_2,\mathbf{k}_2,\mathbf{k}_3,l_2,b_2,i_4,k_4,\mathbf{k}_4,l_4,b_4\right)=\pi\left(i_2,k_2,\{k_2\},1,i_2,k_2,\{k_2\},\{k_2\},1,1,i_4,k_4,\{k_4\},1,1\right)$$

takes (Table 5.3).

Table 5.3 The SDMC-contributing factor and normalized SDMC-contributing factor sets, and their corresponding SDMC indices for the (Two resources, One product, Two operations) system in Table 5.2

Row No.	i_2	k_2	i_4	k_4	π	$\tilde{\pi}=\frac{\pi}{Total}$ (Equation 4.7)	SDMC= $-\tilde{\pi}\log_2\tilde{\pi}$ (bits)
1	1	1	1	1	100	0.048	0.209
2	1	1	2	1	100	0.048	0.209
3	1	1	2	2	100	0.048	0.209
4	1	2	1	2	200	0.095	0.323
5	1	2	2	1	200	0.095	0.323
6	1	2	2	2	200	0.095	0.323
7	2	1	1	1	100	0.048	0.209
8	2	1	1	2	100	0.048	0.209
9	2	1	2	1	100	0.048	0.209
10	2	2	1	1	300	0.143	0.401
11	2	2	1	2	300	0.143	0.401
12	2	2	2	2	300	0.143	0.401
Total (lines 1 to 12)					2100	1	3.427

The value that this SDMC-contributing factor takes is calculated as the product of the processing time of operation i_2 on resource k_2 for product l_2, given by $\phi\left(i_2,\mathbf{k}_2,l_2\right)$ in Table 5.2, and its corresponding lot size, $L_{l_2}=L_1=10$ (as there are no assembly/disassembly operations, the lot size does not depend on the operation).

The meaning of the elements of Table 5.3 is discussed next:

- The diagonal elements corresponding to the four combinations (operation, resource) are initialised in the rows 1, 4, 9 and 12.
- The rows 2-3 and 5-6 model the relationship between operation 1 on resource 1 and resource 2, respectively, and the alternative operation 2, on resource 1 and resource 2, respectively.
- The rows 7-8 and 10-11 model the relationship between operation 2 on resource 1 and resource 2, respectively, and the alternative operation 1, on resource 1 and resource 2, respectively.

The algorithm for these initialisations is presented in Figure 4.5, and their justification is given in Section 4.5.4.

The value of the SDMC obtained using the algorithm presented in Section 4.5.4 is 3.4273 bits. This is obtained by firstly normalizing all the elements π in Table 5.3, and thus generating the normalized SDMC-contributing factor set, the values of which are also presented in column $\tilde{\pi}$ of Table 5.3. Then, the SDMC formula in Equation 4.9 is used to calculate the SDMC corresponding to each element (column $-\tilde{\pi}\log_2\tilde{\pi}$ in Table 5.3).

Using the grouping axiom [Ash65] (EA5 and Equation 2.3), we can also separately perform an operation-based analysis and a resource-based analysis of SDMC. The results thus obtained indicate that:

- Operation 1 contributes to the total SDMC with 1.5967 bits (obtained by adding all the SDMC values corresponding to $i_2 = 1$ in Table 5.3), and operation 2 with 1.8306 bits (obtained by adding all the SDMC values corresponding to $i_2 = 2$ in Table 5.3).

- Resource 1 contributes to the total SDMC with 1.2549 (obtained by adding all the SDMC values corresponding to $k_2 = 1$ in Table 5.3), and resource 2 with 2.5559 bits (obtained by adding all the SDMC values corresponding to $k_2 = 2$ in Table 5.3).

These results reflect the fact that both operations can be performed on either of the two resources, with operation 2 having a bigger impact on the total SDMC than operation 1. This is explained by the fact that, although both operations can be run on both resource 1 and resource 2, operation 2 has a higher degree of flexibility than operation 1, due to the variability of the processing times that it requires (10, 30), by comparison to (10, 20) for operation 1. This is reflected in the higher SDMC contributions of operation 2 in the rows 10 to 12 than those of operation 1 in the rows 4 to 6. A similar reasoning can be applied to the fact that resource 2 has a bigger impact on the total SDMC than resource 1.The result above quantifies the effect of operation, resource and sequence flexibility on SDMC.

Table 5.4 SDMC for systems with lower flexibility than the reference system (Two resources, One product, Two operations) in Table 5.2

Row No.	$\phi(i,\mathbf{k},l)$				SDMC
	$\phi(1,\{1\},1)$	$\phi(1,\{2\},1)$	$\phi(2,\{1\},1)$	$\phi(2,\{2\},1)$	
1	10	0	0	0	0
2	0	20	0	0	0
3	0	0	10	0	0
4	0	0	0	30	0
5	10	10	0	0	1
6	10	0	10	0	2
7	10	0	0	30	1.8112
8	10	20	10	0	2.7254
9	10	20	0	30	2.6892
10	0	20	10	30	2.6995
11	10	0	10	30	2.594

The effect of precedence constraints on SDMC is discussed in Section 5.1.6. The SDMC values for several systems with lower operation- and resource-flexibility than the system in Table 5.2 are given in Table 5.4.

A non-null $\phi(i,\mathbf{k},l)$ element in Table 5.4 indicates that operation i can be performed on resource subset $\mathbf{k}$. As mentioned earlier in this section, l is always 1 in this example, due to the fact that the system processes only one product type. Each line in Table 5.4 represents a different system configuration, due to different values of $\phi(1,\{1\},1)$, $\phi(1,\{2\},1)$, $\phi(2,\{1\},1)$ and $\phi(2,\{2\},1)$. As the operation processing times for the system configurations in Table 5.4 are comparable (according to the definition in Section 4.6.4), the higher the number of non-null $\phi(i,\mathbf{k},l)$ elements, the more difficult the scheduling decisions will be, and therefore the higher the SDMC.

The examples in Table 5.4 show that:

1. The SDMC of an inflexible system (obtained by removing the flexibility from the system in Table 5.2) is zero (rows 1-4). No decisions have to be made in systems with these configurations.
2. Systems with lower operation flexibility have a lower SDMC (e.g. rows 5-7 versus rows 8-10).
3. Systems with lower resource flexibility have a lower SDMC (e.g. rows 7 versus 9, and 7 versus 11).
4. For the same level of resource and operation flexibility, the SDMC will depend on the processing time required by the operations on specific resources (e.g. rows 5 versus 6, 7 versus 8, and 9 versus 10).

For identical processing times, increasing the number of operations has a bigger impact on the SDMC than increasing the operation flexibility (row 5 versus 6 in Table 5.4). In row 5, the product requires only operation 1, which can be produced on either resource 1 or resource 2 in 10 processing units. In row 6, the product requires two operations, and the flexibility of operation 1 has been removed. The SDMC for row 5 is 1, and for row 6 SDMC is 2. This quantifies the fact that for the system in row 5 there are just two SDM options, i.e. running operation 1 on either resource 1 or 2. Therefore, the normalized SDMC-contributing factor set will have only two identical elements, each contributing 0.5 to the total SDMC. For the system in row 6, the normalized SDMC-contributing factor set will have four identical elements, each contributing 0.5 to the total SDMC. Two of these elements will be diagonal elements, and two will model sequence flexibility.

In this section, we have presented in detail how the SDMC is calculated for systems comprising only processing operations. The system in this example will be used as a reference for discussion of the impact of varying the parameters of the system on SDMC, in Sections 5.1.2 to 5.1.9.

5.1.2 The effect of the number of operations and resource sharing on SDMC (Two resources, One product, Four operations)

Let us now increase the number of operations for the system presented in Section 5.1.1, whilst keeping the other parameters identical. To make the results easier to compare and assess, we have added two extra operations, 3 and 4. As shown in Table 5.5, operation 3 has the same resource and processing time specification as operation 1, and operation 4 has the same specifications as operation 2 in the reference system. In the new configuration, both resource 1 and resource 2 can be used for all four operations. We therefore increase the resource flexibility.

The system in this example has only processing operations with no precedence constraints, and therefore the discussion presented in Section 5.1.1 on the manner of calculating the elements of SDMC-contributing factor set is valid for the new configuration. The SDMC-contributing factor set has now 56 elements, and the SDMC obtained for this example is 5.6497. Operations 1 and 3 contribute to the complexity by 1.2746 bits each, and operations 2 and 4 by 1.5502 bits each. A similar resource-based analysis as performed in Section 5.1.1 shows that resource 1 contributes to the total SDMC by 1.8899 bits, whereas the contribution of resource 2 is of 3.7598 bits.

Table 5.5 Specification of the two operations added to the reference system in Table 5.2

Product ($l=\overline{1,n}$)	Operation ($i=\overline{1,m}$)	Resource k	Resource subset $\mathbf{k}$	$(i,\mathbf{k},l)$	$\phi(i,\mathbf{k},l)$
1	3	1	$\{1\}$	$(1,\{1\},1)$	10
	3	2	$\{2\}$	$(1,\{2\},1)$	20
	4	1	$\{1\}$	$(2,\{1\},1)$	10
	4	2	$\{2\}$	$(2,\{2\},1)$	30

Although there has been no change in the manner in which operation 1 and operation 2 are specified, their absolute values are lower than those obtained in Section 5.1.1 (1.5967 and 1.8306, respectively). This reflects the fact that, due to the identical requirements of operation 1 and operation 3, it will be easier to decide between the two. The same remark applies to operations 2 and 4. The contribution of each element within a flexibility class (such as operation or resource) to the total SDMC is assessed in relation to the specifications of all the other elements within the same class. Therefore, as for any information-theoretic measure, the SDMC has additive properties only for independent components. This remark also justifies why the absolute SDMC values of resources 1 and 2 in the augmented system are higher than those corresponding to the reference system in Section 5.1.1 (1.2549 and 2.5559, respectively). The level of potential demand (and therefore the flexibility) placed on each of resource 1 and 2 in this example is twice their corresponding level in Section 5.1.1. This fact, and the length of processing time that may be required by each task, are reflected in the new values of SDMC associated with each resource.

This example shows that:

- The number of non-null SDMC-contributing factors increases with an increase in the number of operations.
- For comparable operation times, the SDMC increases with an increase in the number of operations.
- An increase in resource flexibility increases the SDMC.
- Identically specified operations contribute the same amount to the SDMC.
- Every time a new element (resource, operation or product), linked in any way to the existing elements, is introduced in the system, the overall assessment of any global information-theoretic of complexity (including the SDMC) of the newly obtained system has to be performed again.

5.1.3 The effect of the number of resources on SDMC

5.1.3.1 Four resources, One product, Two operations

In this section, we will add two new resources (indexed 3 and 4) to the system analysed in Section 5.1.1, as presented in Table 5.6. We therefore increase the operation flexibility, as the number of operations and products are as in the reference system.

Table 5.6 Two resources added to the system in Table 5.2 (Two resource, One Product, Two operations)

Product ($l=\overline{1,n}$)	Operation ($i=\overline{1,m}$)	Resource k	Resource subset $\mathbf{k}$	$(i,\mathbf{k},l)$	$\phi(i,\mathbf{k},l)$
1	1	3	$\{3\}$	$(1,\{3\},1)$	10
	1	4	$\{4\}$	$(1,\{4\},1)$	20
	2	3	$\{3\}$	$(2,\{3\},1)$	10
	2	4	$\{4\}$	$(2,\{4\},1)$	30

As there is no resource concurrency, the resource subsets will again comprise a single resource. The total system specification, obtained by merging Table 5.2 and Table 5.6, is an example of system specification for identical resources. Indeed, resource 1 and resource 3 can both process operation 1, in identical processing times. The same remark is also true for resource 2 and resource 4, with respect to operation 2.

This example has 40 non-null SDMC-contributing factors, and the total SDMC is 5.1643 bits, which is 1.737 bits higher than the SDMC of the reference system. This difference quantifies the additional operation flexibility embedded in the system. This interpretation is confirmed by the results presented in Table 5.7, where both operations 1 and 2 have higher SDMC values than those corresponding to the reference system.

Table 5.7 Operation- and Resource-based comparisons between Section 5.1.3.1 (Four resources, One Product, Two Operations) and Section 5.1.1 (Two resources, One Product, Two Operations)

SDMC		Section 5.1.3.1	Section 5.1.1
Operation-based analysis	Operation 1	2.3411	1.5967
	Operation 2	2.8232	1.8306
Resource-based analysis	Resource 1	0.8756	1.2549
	Resource 2	1.7065	2.5559
	Resource 3	0.8756	N/A
	Resource 4	1.7065	N/A
Total		5.1643	3.4273

5.1.3.2 Four resources, One product, Four operations

A second analysis to reflect the effect of additional resources on the total SDMC consists of adding two new operations and two new resources (indexed 3 and 4), to the configuration in Section 5.1.1 (Two resources, One product, Two operations), with operations 3 and 4 specified as in Table 5.8.

Table 5.8 Two resources and two operations added to the system in Section 5.1.1 (Two resources, One Product, Two Operations)

Product ($l=\overline{1,n}$)	Operation ($i=\overline{1,m}$)	Resource k	Resource subset $\mathbf{k}$	$(i,\mathbf{k},l)$	$\phi(i,\mathbf{k},l)$
1	3	3	$\{3\}$	$(3,\{3\},1)$	10
	3	4	$\{4\}$	$(3,\{4\},1)$	20
	4	3	$\{3\}$	$(4,\{3\},1)$	10
	4	4	$\{4\}$	$(4,\{4\},1)$	30

Operations 1 and 3, and operations 2 and 4 have the same degree of flexibility and the same processing times. Also, resources 1 and 3, and 2 and 4 have the same degree of flexibility.

The total SDMC in this case is 5.6497 bits, which is identical with the SDMC in Section 5.1.2 (Two resources, One Product, Four Operations). This reflects the fact that the number and types of decisions and the processing times of the tasks that have to be decided upon are identical for the system in this example and that in Section 5.1.2. The fact that the SDM set obtained for this example is identical to that in Section 5.1.2 further confirms the correctness of the algorithm for the definition of the SDMC-contributing factors, and of the results it provides. The operation-based analysis also provides results identical with those obtained for Section 5.1.2, whereas the resource-based analysis shows, unsurprisingly, that resources 1 and 3 each contribute with half of the SDMC associated with resource 1 in Section 5.1.2, (i.e. with 0.9449 bits) to the total SDMC. Similarly, resources 2 and 4 have the same contribution, 1.8799 bits, to the total SDMC, and the SDMC associated with any of these resources represents half of the SDMC corresponding to resource 2 in Section 5.1.2. This shows that the potential demands placed upon resources 1 and 3, and resources 2 and 4, respectively, are identical.

The examples in Sections 5.1.3.1 and 5.1.3.2 have shown that:

- The number of non-null SDMC-contributing factors increases with an increase in the number of resources.
- For comparable operation times, the SDMC increases with an increase in the number of resources.
- Identical resources can be successfully modelled by the method presented in Section 4.5.
- Identically loaded resources contribute the same amount to the SDMC (Resources 1 and 3, and 2 and 4 in Sections 5.1.3.1 and 5.1.3.2).

5.1.4 The effect of resource concurrency on SDMC

We now go back to Section 5.1.1, and rather than adding an operation or a resource, we increase the flexibility of operation 1 by adding an extra option for it: this operation may now also run simultaneously on resources 1 and 2, with a processing time of five time units. The complete specification for the new system is given in Table 5.9.

There are 22 non-null SDMC-contributing factors for the system in this example and, due to the presence of resource concurrency, the resource sets $\mathbf{k}_2$ and $\mathbf{k}_4$ now become relevant for the modelling (as shown in Table 5.10). The remainder of the discussion on the manner of calculating the SDMC-contributing factors presented in Section 5.1.1 is valid for this section. The complete set of non-null SDMC-contributing factors for the system in this section is given in Table 5.10.

The elements in rows 1 to 12 in Table 5.10 are identical with those in Table 5.3, Section 5.1.1, and rows 13 to 22 are generated due to the resource concurrency introduced in the system in this example. For all resources that need to be simultaneously used for this operation, the initialisation of the diagonal elements ($i_2 = i_4,\ k_2 = k_4,\ \mathbf{k}_2 = \mathbf{k}_4$) is performed (rows 13 and 14 in Table 5.10).

Table 5.9 Resource concurrency: Extra operation flexibility added to the system in Table 5.2 (Two resources, One Product, Two Operations)

Product ($l=\overline{1,n}$)	Operation ($i=\overline{1,m}$)	Resource k	Resource subset $\mathbf{k}$	$(i,\mathbf{k},l)$	$\phi(i,\mathbf{k},l)$
1	1	1	$\{1\}$	$(1,\{1\},1)$	10
	1	2	$\{2\}$	$(1,\{2\},1)$	20
	1	1	$\{1,2\}$	$(1,\{1,2\},1)$	5
	1	2	$\{1,2\}$	$(1,\{1,2\},1)$	5
	2	1	$\{1\}$	$(2,\{1\},1)$	10
	2	2	$\{2\}$	$(2,\{2\},1)$	30

As described in Section 5.1.1, the value of an SDMC-contributing factor for a processing operation is calculated as the product of the processing time of operation i_2 on resource k_2 for product l_2 and its lot size. The elements in rows 13 to 22 of Table 5.10 correspond to the decisions faced by the decision maker in relation to the concurrent utilisation of resources 1 and 2 for operation 1, and will be discussed next.

When defining the non-null SDMC-contributing factors corresponding to an operation i_2 which has to be performed on more than one resource, as defined by resource subset $\mathbf{k}_2$, the diagonal elements (for which $\mathbf{k}_2=\mathbf{k}_4$) will only be initialised for $i_2=i_4$, $\mathbf{k}_2=\mathbf{k}_4$, $l_2=l_4$ and $b_2=b_4$. This corresponds to the fact that there is no option for running operation i_2 for the same product type and batch number on any two resources in resource subset $\mathbf{k}_2$, so there is no decision to be made. All the resources in $\mathbf{k}_2$ have to be used simultaneously for operation i_2. Resource concurrency is thus modelled in a realistic and meaningful manner. This rule is applied whenever an operation (either processing or set-up) requires more than one resource.

Table 5.10 The SDMC-contributing factors for the system presented in Table 5.9

Row No.	i_2	k_2	$\mathbf{k}_2$	i_4	k_4	$\mathbf{k}_4$	π	$\tilde{\pi} = \frac{\pi}{Total}$	SDMC=$-\tilde{\pi}\log_2\tilde{\pi}$
1	1	1	$\{1\}$	1	1	$\{1\}$	100	0.031	0.156
2	1	1	$\{2\}$	2	1	$\{1\}$	100	0.031	0.156
3	1	1	$\{2\}$	2	2	$\{2\}$	100	0.031	0.156
4	1	2	$\{1\}$	1	2	$\{2\}$	200	0.063	0.250
5	1	2	$\{2\}$	2	1	$\{1\}$	200	0.063	0.250
6	1	2	$\{2\}$	2	2	$\{2\}$	200	0.063	0.250
7	2	1	$\{1\}$	1	1	$\{1\}$	100	0.031	0.156
8	2	1	$\{1\}$	1	2	$\{2\}$	100	0.031	0.156
9	2	1	$\{2\}$	2	1	$\{1\}$	100	0.031	0.156
10	2	2	$\{1\}$	1	1	$\{1\}$	300	0.094	0.320
11	2	2	$\{1\}$	1	2	$\{2\}$	300	0.094	0.320
12	2	2	$\{2\}$	2	2	$\{2\}$	300	0.094	0.320
13	1	1	$\{1,2\}$	1	1	$\{1,2\}$	50	0.016	0.094
14	1	2	$\{1,2\}$	1	2	$\{1,2\}$	50	0.016	0.094
15	1	1	$\{1,2\}$	2	1	$\{1\}$	50	0.016	0.094
16	1	2	$\{1,2\}$	2	1	$\{1\}$	50	0.016	0.094
17	1	1	$\{1,2\}$	2	2	$\{2\}$	50	0.016	0.094
18	1	2	$\{1,2\}$	2	2	$\{2\}$	50	0.016	0.094
19	2	1	$\{1\}$	1	1	$\{1,2\}$	100	0.031	0.156
20	2	1	$\{1\}$	1	2	$\{1,2\}$	100	0.031	0.156
21	2	2	$\{2\}$	1	1	$\{1,2\}$	300	0.094	0.320
22	2	2	$\{2\}$	1	2	$\{1,2\}$	300	0.094	0.320
Partial Sum1 (lines 1 to 12)							2100	Not relevant	2.648
Partial Sum2 (lines 13 to 22)							1100	Not relevant	1.515
Total (lines 1 to 22)							3200	1	4.163

The total SDMC for this example is 4.1632 bits, with 0.7359 higher than the SDMC obtained for the reference system in Section 5.1.1. The SDMC corresponding to operation 1 is 1.7812, and that of operation 2 is 2.3820. Both values are higher than those corresponding to the same operations of the reference system (1.5967 bits and 1.8306 bits, respectively). These increases in SDMC values quantify the increase in operation flexibility for operation 1, and the associated effect this has on operation 2, through their common potential use of resources 1 and 2. The resource-based analysis gives a SDMC of 1.5312 for resource 1, and 2.6320 for resource 2 (with 1.2549 and 2.5559 being their corresponding values for the reference system. A higher relative increase is obtained for resource 1 by comparison to resource 2, with reference to the values obtained for the reference system. This is due to the fact that the processing times required by any of the operations on resource 1 (10, 5, 10) are closer together (i.e. more clustered), than those on resource 2 (20, 5, 30). Therefore, due to the comparable processing times and to the normalization applied to the SDMC-contributing factors (Section 4.5.5), the new option for operation 1 will have a bigger relative impact on the SDMC of resource 1 than on the SDMC of resource 2.

This example has shown that:

- The number of non-null SDMC-contributing factors increases with resource concurrency.
- For comparable processing times, SDMC increases with resource concurrency.
- Resource concurrency has an impact on the SDMC contribution of all operations and resources involved in concurrency.

5.1.5 The effect of the number of products on SDMC

In this example we will add a new product, indexed 2, to the reference system introduced in Section 5.1.1, whilst keeping the number of operations and resources constant. Product 2 has to be produced in one batch of size 10, therefore $Q_2 = L_2 = 10$. There are no precedence constraints in the system.

The specifications for the new system are presented in Table 5.11. The SDMC for this example is 4.8074, which is with 1.3801 bits higher than the SDMC obtained for the reference system. The SDMC-contributing factor set has 32 non-null elements, i.e. 20 more elements than the reference system (Table 5.3). This significant increase is explained by an increased flexibility in the options faced by the decision maker. As no precedence constraints are defined for the system in this example, any of the operations of any of the products can be performed at any given time.

Table 5.11 The Two Products, Two resources, Two operations system

Product ($l=\overline{1,n}$)	Operation ($i=\overline{1,m}$)	Resource k	Resource subset $\mathbf{k}$	$(i,\mathbf{k},l)$	$\Phi(i,\mathbf{k},l)$
1	1	1	$\{1\}$	$(1,\{1\},1)$	10
	1	2	$\{2\}$	$(1,\{2\},1)$	20
	2	1	$\{1\}$	$(2,\{1\},1)$	10
	2	2	$\{2\}$	$(2,\{2\},1)$	30
2	1	1	$\{1\}$	$(1,\{1\},1)$	40
	1	2	$\{2\}$	$(1,\{2\},1)$	15

Intuitively, the complexity associated with product 1 is higher than that associated with product 2, as product 1 has more options associated with its operations. This view is confirmed by the product-based analysis, which shows that products 1 and 2 contribute to the total SDMC with 2.6365 bits and 2.1709 bits, respectively.

The operation-based analysis indicates operation 1 as the highest contributor to the decision-making complexity, with 2.6383 bits, with the remainder of 2.1690 bits due to operation 2. The processing demand is relatively evenly distributed on the system resources, with 2.3378 bits associated with resource 1, and 2.4696 with resource 2.

This example has shown that:

- The number of non-null SDMC-contributing factors increases with an increase in the number of products.
- For comparable operation times, the SDMC increases with an increase in the number of products.

5.1.6 The effect of operation precedence on SDMC

Let us now reduce sequence flexibility by introducing a precedence constraint for the reference system in Section 5.1.1: operation 1 has to precede operation 2. The precedence requirement set (Section 4.5.3.5) has now one element $\gamma(1,1,1,2,1,1)=1$, which encodes the fact that operation 1 of batch 1 of product 1 has to precede operation 2 of batch 1 of product 1. Due to this constraint, and as described in Step 3 of the algorithm (Figure 4.5), all the elements in Table 5.3 for which $i_2 = 2$ and $i_4 = 1$ will now become null. The SDMC-contributing factor set has only 8 elements, with the elements in rows 7, 8, 10 and 11 in Table 5.3 becoming null. The SDMC obtained for this example is 2.8731. The structure of this SDMC is presented in Table 5.12.

Table 5.12 Operation- and Resource-based comparison between Section 5.1.6 (The effect of operation precedence) and the reference system in Section 5.1.1

SDMC	Operation 1	Operation 2	Resource 1	Resource 2	*Total*
Section 5.1.6	2.1003	0.7728	1.1385	1.7345	2.8731
Section 5.1.1	1.5967	1.8306	1.2549	2.5559	3.4273

Due to the precedence constraints, there is now less flexibility in the system, in terms of the number of possible options of the order of running an operation. This is reflected first in a reduced value of the total SDMC by comparison to Section 5.1.1 (the *Total* column in Table 5.12). Second, operation 1 has now a significantly higher complexity, as the decision maker will need to refer to operation 2 when making decisions about it. The decision maker will not have to consider operation 1 when the current operation is operation 2, due to the precedence constraint introduced in the system. The considerable reduction in the ratio of the contribution made by resource 2 to the total by comparison to Section 5.1.1 is also explained by the precedence constraint, and by the overall structure of the system, in terms of operation flexibility and processing times (Table 5.2).

An important remark is that precedence constraints can be defined between operations, products and batches. Any additional precedence constraint will determine a further reduction in the total SDMC.

This example has shown that SDMC and the number of non-null SDMC-contributing factors decrease with an increase in the number of precedence constraints in the system.

5.1.7 The effect of lot sizes on SDMC

Let us now go back to Section 5.1.1, and choose that product 1 is produced in 2 batches of 5 products each ($Q_1 = 10$ and $q_1 = L_1 = 5$), and investigate the effect of lot flexibility on SDMC. If we introduce no precedence constraints between batches, the SDMC-contributing factor set will have 56 elements, with an associated value of 5.6497. If we then choose to have 5 batches ($Q_1 = 10$ and $q_1 = L_1 = 2$), the SDMC-contributing factor set will have 380 elements, and the SDMC will be significantly higher, i.e. 8.412. This quantifies an increase in the number of SDM options.

If we then introduce precedence constraints of the form $b_x \rightarrow b_y$, $x = \overline{1, Q_1/L_1}, y = \overline{1, Q_1/L_1}$ and $x < y$ (i.e. only allow one batch in the system at any given time), the new value for the SDMC is 7.6237 (Table 5.13). This will reduce the amount of WIP allowed in the system at any given time. The chosen lot sizing strategy will impact on the amount of WIP in the system, as well as on SDMC.

Table 5.13 The effect of the lot sizing policy on SDMC

SDMC	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Number of non-null elements of the SDMC-contributing factor set	*Total*
2 batches, no precedence	2.8248	2.8248	N/A	N/A	N/A	56	5.6497
2 batches, precedence	3.6150	1.5492	N/A	N/A	N/A	40	5.1642
5 batches, no precedence	1.6824	1.6824	1.6824	1.6824	1.6824	380	8.4122
5 batches, precedence	2.6336	2.0791	1.5247	0.9702	0.4158	220	7.6237
Section 5.1.1, one batch	3.4273	N/A	N/A	N/A	N/A	N/A	3.4273

This example has shown that:

- SDMC and the number of non-null elements of the SDMC-contributing factor set increase with the increase in the lot sizes.
- Precedence constraints can be used as a means of controlling the trade-off between the level of flexibility and the level of WIP in the system.

5.1.8 The effect of sequence-dependent set-up operations on SDMC

In this section we will exemplify the manner in which the sequence-dependent set-ups are modelled in the system, and their impact on SDMC. For simplicity and clarity, we define just one additional set-up operation for the system in Table 5.2, as defined in Table 5.14. As a reminder, a non-null set-up time requirement element $st(i_1,k,\mathbf{k}_1,l_1,\mathbf{k}_2,i_3,\mathbf{k}_3,l_3)$ represents the set-up time of resource k for processing operation i_3 of product l_3 on resource subset $\mathbf{k}_3$. The previous operation on resource k is i_1 for product l_1 as part of resources $\mathbf{k}_1$. The set-up operation of resource k will be performed using all the resources in set $\mathbf{k}_2$. k should therefore belong to all $\mathbf{k}_1$, $\mathbf{k}_2$ and $\mathbf{k}_3$.

According to Table 5.14, a single situation requires set-up: resource 2 has to be set up for operation 2 by using both resources 1 and 2 (resource subset $\mathbf{k}_2 = \{1,2\}$). The set-up is only required when the previous operation on resource 2 is operation 1.

Table 5.14 The set-up time requirement set for Section 5.1.8 (The effect of sequence-dependent set-up operations)

i_1	k	$\mathbf{k}_1$	l_1	$\mathbf{k}_2$	i_3	$\mathbf{k}_3$	l_3	$st(i_1,k,\mathbf{k}_1,l_1,\mathbf{k}_2,i_3,\mathbf{k}_3,l_3)$
1	2	$\{2\}$	1	$\{1,2\}$	2	$\{2\}$	1	5

Before calculating the elements of the SDMC-contributing factor set, the precedence requirement set (which was so far null) needs to be extended to include the set-up operation (Section 4.5.3.7). The index of the set-up of operation i is calculated as $(m+i)$, therefore the index of the set-up for operation 2 is $(2+2)=4$. The precedence requirement set will have one element, $\gamma(4,1,1,2,1,1)=1$ (set-up operation 4 has to precede processing operation 2). The 24 non-null elements of the SDMC-contributing factor set are given in Table 5.15. For clarity, only the relevant indices are shown in Table 5.15, therefore l_1, l_2 and l_4, and b_2 and b_4 are omitted, as all of them are always 1 for this example. The elements in rows 1 to 12 are identical with the elements in Table 5.3, and model the relationship between processing operations that do not require set-up. They are initialised according to Step 3 of the algorithm in Section 4.5.6. Due to the introduction of the set-up operation, the indices i_1, k, $\mathbf{k}_1$, $\mathbf{k}_2$, $\mathbf{k}_3$ and $\mathbf{k}_4$ have now become relevant to the modelling. According to the Step 3 of the algorithm in Section 4.5.6, for modelling the relationship *processing operations* versus *processing operations* $i_1 = i_2$, $k = k_2$, $\mathbf{k}_1 = \mathbf{k}_2 = \mathbf{k}_3$. These relationships are true for the elements in rows 1 to 12 of Table 5.15.

Then, for all the resources that have to be used for set-up, we have to initialise the main diagonal elements, as described in Step 1 of the algorithm in Section 4.5.6. This is done in rows 13 and 14 of Table 5.15. As presented in the description of the indices of the SDMC-contributing factors in Section 4.5.6, when the current operation i_2 is a set-up operation, the corresponding SDMC-contributing factor refers to the set-up operation i_2 of the current resource k for processing operation $(i_2 - m)$ on resource subset $\mathbf{k}_3$, when the previous operation on k was operation i_1 as part of resource subset $\mathbf{k}_1$ for product l_1. All the resources k_2 in resource subset $\mathbf{k}_2$ are used for set-up.

Rows 15 to 20 model the relationship between *the set-up for operation 2* versus *the processing operations 1 and 2* that do not require set-up. The SDMC-contributing factors corresponding to the relationship between the set-up for operation 2 and the alternative operation 2 on resource subset 2 as defined in Table 5.14 are null, as there is no option on the order of executing them. This corresponds to the actions that the decision maker would take in such a situation, i.e. not even to consider running a processing operation (and therefore looking up information about it) before it has been set up. Also, the SDMC-contributing factors corresponding to the relationship between operation 2 on resource subset 2 and the alternative set-up for operation 2 as defined in Table 5.14 are null, due to the precedence relationship between set-up for operation 2 and operation 2. This procedure realistically and innovatively models the intrinsic relationships and dependences between a set-up operation and its corresponding processing operation.

Last, rows 21 to 24 model the relationship between processing operation 1 and the set-up operation in the system.

Table 5.15 The SDMC-contributing factor set for the sequence-dependent set-up operations

Row No.	i_1	k	$\mathbf{k}_1$	i_2	k_2	$\mathbf{k}_2$	$\mathbf{k}_3$	i_4	k_4	$\mathbf{k}_4$	π	$\tilde{\pi} = \frac{\pi}{Total}$	SDMC= $-\tilde{\pi}\log_2\tilde{\pi}$
1	1	1	{1}	1	1	{1}	{1}	1	1	{1}	100	0.036	0.174
2	1	1	{1}	1	1	{1}	{1}	2	1	{1}	100	0.036	0.174
3	1	1	{1}	1	1	{1}	{1}	2	2	{2}	100	0.036	0.174
4	1	2	{2}	1	2	{2}	{2}	1	2	{2}	200	0.073	0.276
5	1	2	{2}	1	2	{2}	{2}	2	1	{1}	200	0.073	0.276
6	1	2	{2}	1	2	{2}	{2}	2	2	{2}	200	0.073	0.276
7	2	1	{1}	2	1	{1}	{1}	1	1	{1}	100	0.036	0.174
8	2	1	{1}	2	1	{1}	{1}	1	2	{2}	100	0.036	0.174
9	2	1	{1}	2	1	{1}	{1}	2	1	{1}	100	0.036	0.174
10	2	2	{2}	2	2	{2}	{2}	1	1	{1}	300	0.109	0.349
11	2	2	{2}	2	2	{2}	{2}	1	2	{2}	300	0.109	0.349
12	2	2	{2}	2	2	{2}	{2}	2	2	{2}	300	0.109	0.349
13	1	2	{2}	4	1	{1,2}	{2}	4	1	{1,2}	5	0.002	0.017
14	1	2	{2}	4	2	{1,2}	{2}	4	2	{1,2}	5	0.002	0.017
15	1	2	{2}	4	1	{1,2}	{2}	1	1	{1}	5	0.002	0.017
16	1	2	{2}	4	2	{1,2}	{2}	1	1	{1}	5	0.002	0.017
17	1	2	{2}	4	1	{1,2}	{2}	1	2	{2}	5	0.002	0.017
18	1	2	{2}	4	2	{1,2}	{2}	1	2	{2}	5	0.002	0.017
19	1	2	{2}	4	1	{1,2}	{2}	2	1	{1}	5	0.002	0.017
20	1	2	{2}	4	2	{1,2}	{2}	2	1	{1}	5	0.002	0.017
21	1	1	{1}	1	1	{1}	{1}	4	1	{1,2}	100	0.036	0.174
22	1	1	{1}	1	1	{1}	{1}	4	2	{1,2}	100	0.036	0.174
23	1	2	{2}	1	2	{2}	{2}	4	1	{1,2}	200	0.073	0.276
24	1	2	{2}	1	2	{2}	{2}	4	2	{1,2}	200	0.073	0.276
Total (Rows 1 to 24)											2740	1	3.954

As explained in the description of Step 4 of the algorithm for the initialisation of the SDMC-contributing factors, there is no alternative associated with operation 2 versus its set-up operation, and therefore the SDMC-contributing factors corresponding to these configurations are null. The operation- and resource-based analyses of the structure of the SDMC are presented in Table 5.16.

Table 5.16 Operation- and Resource-based analysis of the effect of sequence-dependent set-ups on SDMC

SDMC	Sequence-dependent set-up (Section 5.1.8)	Reference system (Section 5.1.1)
Set-up	0.1328	N/A
Operation 1	2.2497	1.5967
Operation 2	1.5711	1.8306
Resource 1	1.4609	1.2549
Resource 2	2.4927	2.5559
Total SDMC	3.9536	3.4273

As more constraints have been placed on operation 2 through the sequence-dependent set-up requirements, its corresponding SDMC decreased (Table 5.16). Although there are no constraints between the order of running operation 1 and operation 2, every time resource 2 has been chosen for it, it will need to be set up (unless the previous operation on it was operation 2). The constraint placed on operation 2 therefore affects the flexibility of resource 2, as shown in Table 5.16. The relative value of the set-up time (5) versus the processing times (10 and 20 for resource 1, and 10 and 30 for resource 2) explains the changes in the resource relative contributions to the total SDMC.

This example has shown that:

- The number of non-null SDMC-contributing factors increases with the introduction of sequence-dependent set-up operations.
- For comparable set-up and processing times SDMC increases with the introduction of sequence-dependent set-up operations.

5.1.9 The effect of "famous by duration" operations

This section is dedicated to isolated processing or set-up operations that require a time of several orders of magnitude higher than the other operations. By processing time in this section we mean the operation processing time per product multiplied by its corresponding lot size. For all these situations, the SDMC will decrease rather than increase when adding a new set-up or processing operation. This is explained, analytically, by the change of scale when calculating the SDMC. Due to the introduction of a new element significantly higher than the others, the normalized processing requirement elements $\tilde{\pi}$ corresponding to all the other operations in the system will now be approximately 0, and its corresponding SDMC will also be 0 (Section 4.6.4).

Table 5.17 The effect of significantly higher than the rest processing times on SDMC

Operation	Resource	Resource subset	Processing time	Previous processing time (Section No.)	Previous SDMC (Table No)	New SDMC
3	2	2	20000	20 (Section 5.1.2)	5.6497 (Table 5.5)	2.8756
2	3	3	10000	10 (Section 5.1.3)	5.1643 (Table 5.6)	2.4551

For example, the SDMC corresponding to $\tilde{\pi} = 0.01$ is 0.0664. This means that the previous operations in the system will contribute with smaller amounts to the total SDMC than before the introduction of the new operation. Therefore, if just one operation with processing time higher than the others is introduced, its corresponding $\tilde{\pi}$ element will be close to 1, and the associated entropy will be close to 0 (0.2575 for $\tilde{\pi}$ =0.8, and 0.1368 for $\tilde{\pi}$ =0.9, respectively). Qualitatively, this corresponds to a shift in priorities in the SDM process, which happens every time one or several jobs take significantly more time than the others. This effect is exemplified for processing and set-up operations for several of the examples discussed so far in this chapter (Table 5.17 and Table 5.18).

Table 5.18 The effect of set-up time on SDMC for the system in Section 5.1.8

Set-up time	SDMC
No set-up (Section 5.1.1)	3.4273
0.0001	3.8562
0.001	3.8562
0.01	3.8566
0.1	3.8598
1	3.8827
5	3.9536
50	4.3
100	4.436
500	4.3177
1000	4.03
5000	3.3942
10000	3.2354

Table 5.18 shows that when the set-up time is less than 5000, the SDMC increases. For set-up times of 5000 and higher, SDMC for the augmented system is lower than the SDMC for the reference system.

This section has shown that SDMC decreases by adding set-up or processing times significantly higher than the time of the existing operations.

Section 5.1 has illustrated the application of the SDMC computation method for several classes of devised systems, emphasising the particularities associated with each class, such as operation, resource and sequence flexibility, resource concurrency or sequence-dependent set-up.

5.2 The computation and analysis of SDMC, SC and OC for an example system

In this section we devise a simple example on which we perform the joint SDNC, SC and OC analysis with the aim to identify and assess critical issues. We first interpret the results of each complexity class (SDMC, SC and OC), and then integrate them.

5.2.1 Description of the investigated system

The investigated manufacturing system consists of 4 resources, which during the analysed period have to produce 3 types of products, the details of which are given in Table 5.19. No set-up time is required for any of the resources. As presented in Table 5.19, Product A and Product B are characterized by both resource and processing time flexibility. The highest sequence flexibility is displayed by product B, with no precedence constraint defined between its two operations. Product C has the next highest sequence flexibility, with operation 2 having to precede operation 3. Product A has no sequence flexibility.

Table 5.19 The product, resource and operational requirement sets for a devised system

Product Type	Operational Precedence	Number of Products required	Operation Number	Resources			
				1	2	3	4
A	$1 \rightarrow 2 \rightarrow 3 \rightarrow 4$	10	1	10	20	10	25
			2	23	14		
			3		15	33	5
			4	19			
B	No precedence	5	1		20	20	
			2				20
C	$2 \rightarrow 3$	10	2		31		
			3			33	
			4	43			

5.2.2 Computation of scheduling-related decision-making complexity

The proposed system has four operations (m=4), three products (n=3) and four resources (r=4). The product operational requirements and the operation precedences are defined in Table 5.19. As no resource set-up is required, no such information needs to be included in the input data.

As presented in Section 4.5.4 and illustrated in Section 5.1, the SDMC framework allows for the modelling of various lot sizing policies and precedence constraints. For the example in Table 5.19, the SDMC values for four representative lot sizing policies were calculated using the same computer tool that generated the results for the examples in Section 5.1. These results are presented in Table 5.20.

The capabilities of the SDM framework to integrate structural parameters (such as the number and types of resources, the number and types of products and their required operations) and operational parameters (such as precedence constraints and lot sizing policies) are exemplified in Table 5.20. Most importantly, a transparent and objective link between these parameters is thus established. The insights provided by the method can be used to decide on system or product design, or on operational policies.

The lot-based decision-making row in Table 5.20 refers to producing each product in only one batch, and therefore making scheduling decisions for each operation of each product only once. The second row, with lot size 5, requires scheduling decisions being made twice for product A and C. The product-based SDM will schedule one product at a time, and therefore 10, 5 and 10 scheduling decisions have to be made for A, B and C, respectively. The final configuration in Table 5.20 imposes additional precedence constraints between batches of a given product. Its corresponding SDMC value is therefore lower than that obtained for the product-based SDM.

Table 5.20 The SDMC values for various lot sizing policies and precedence constraints

SDM Scenario	Number of non-null SDMC-contributing factors	Number of non-null precedence requirements	Product Type	Number of products required	Lot size	Total SDMC
Lot-based SDM	198	7	A	10	10	7.4125
			B	5	5	
			C	10	10	
Lot size of 5	727	14	A	10	5	9.3453
			B	5	5	
			C	10	5	
Product-based SDM	20455	70	A	10	1	14.156
			B	5	1	
			C	10	1	
Product-based SDM, one product of a specific type at a time	18920	405	A	10	1	14.045
			B	5	1	
			C	10	1	

The data in Table 5.20 further validate the conceptual and analytical definitions of the SDMC provided in Section 4.5. SDMC represents a measure of the volume, structure and constraints that the scheduler has to deal with in the scheduling phase. Although the variation trend of SDMC and of the number of non-null SDMC-contributing factors are similar (and opposite to the trend of variation of the number of precedence requirement elements), the relative increase of SDMC is much lower than the increase in the number of SDMC-contributing factors. This feature highlights the fact that SDMC integrates not only the volume and constraints of the information used in the SDM stage, but its contents too.

Table 5.21 The specific contributions to the total SDMC for the system in Table 5.19

SDM Scenario/ SDMC	Product Type/ SDMC	Operation Number	Machines			
			1	2	3	4
Lot-based decision-making	A/ 3.527	1	0.284	0.5021	0.284	0.6011
		2	0.4757	0.3175		
		3		0.2443	0.4615	0.0975
		4	0.2593			
	B/ 1.004	1		0.3276	0.3276	
		2				0.3495
	C/ 2.88	2		0.8785		
		3			0.8654	
		4	1.1363			
	Resource-based SDMC		2.1553	2.27	1.9385	1.0481
Lot size of 5	A/ 4.94	1	0.3462	0.6274	0.3462	0.7581
		2	0.6521	0.427		
		3		0.396	0.773	0.152
		4	0.462			
	B/ 1.023	1		0.337	0.337	
		2				0.349
	C/ 3.377	2		1.0136		
		3			1.0313	
		4	1.3323			
	Resource-based SDMC		2.7926	2.801	2.4875	1.2591
Product-based SDM	A/ 7.958	1	0.4971	0.9298	0.4971	1.1363
		2	1.0304	0.6645		
		3		0.6921	1.406	0.2553
		4	0.8503			
	B/ 1.4175	1		0.4714	0.4714	
		2				0.4747
	C/ 4.7699	2		1.4071		
		3			1.4778	
		4	1.885			
	Resource-based SDMC		4.2628	4.1649	3.8523	1.8663

Also, the results in Table 5.20 prove that the SDMC of the product-based scheduling policy is significantly more complex than the lot-based scheduling. This reflects the increase in the number of decisions to be made in the product-based scenario. On the other hand, a product-based or a small lot-size SDM policy decreases the levels of WIP in the system and the product lead time (Section 5.1.7). This illustrates how the SDMC assessment method proposed in this thesis can be used for quantifying the trade-offs between SDMC and classical performance measures in manufacturing.

The visibility and hierarchical decomposition capabilities of the SDMC measure are also demonstrated through the results in Table 5.21 The individual contribution of the SDMC-contributing factors to the total SDMC can be assessed at the required level of detail: Operation-, Resource-, Product-, or any combinations of the three, such as (*Operation*, *Part*, *Resource*) (Table 5.21).

The results presented in Table 5.20 and Table 5.21 confirm the capabilities of the SDMC to quantify the volume and variety of information that the scheduler has to deal with in order to create the schedule:

- The number of different types of products and, for each of them, the number of different operations;
- The total number of products to be produced;
- The number of resources;
- The precedence requirements;
- The processing time flexibility;
- The lot sizes.

In order to further validate the SDMC framework presented in Section 4.5, an additional software tool to calculate the complexity results obtained by applying Deshmukh's method (Section 2.8) has been written in the C programming language. The main specific differences between the methods considered in Table 5.22 consist of the manner in which the lot sizing strategy, the precedence relationships between batches, and the part similarities are modelled.

Table 5.22 Comparison between SDMC and the complexity obtained by Deshmukh method (Section 2.8)

Decision-making scenario	Complexity	
	Deshmukh method	SDMC Assessment method in Section 4.5
Product-based decision-making	N/A	14.156
Lot size of 5	N/A	9.345
Lot-based decision-making	5.048	7.412

The increase in the SDMC obtained by the method presented in this thesis (Section 4.5) in comparison to Deshmukh's method is mainly due to the integrative manner in which the SDMC assessment method has considered all the parts in relationship to each other in the SDM stage. Furthermore, the effect of various lot sizing strategies on a scheduling horizon could not be implemented and assessed in Deshmukh's approach (Section 2.8).

5.2.3 Computation of structural complexity

The time length for which the system is scheduled is 1070, which is the minimum time required to produce Product C. The operating schedule for the exemplified system is presented in Table 5.23.

The calculations of the SC associated with the schedule in Table 5.23 are presented in Table 5.24. The indices I and II in Table 5.24 correspond to the two levels of detail considered for the state definitions. The distinction is made at the *Run* state level of each resource. Index I corresponds to the state being defined by the product and its associated operation currently on a resource being in the *Run* state. Index II captures information about whether a resource is running or not. Intuitively, more complexity is associated with the first scenario.

Table 5.23 A lot-based schedule for the exemplified system

Resource	Job			Start Time	Duration	End Time
	State	Product	Operation			
Resource 1	Run	C	4	0	430	430
		A	1	430	100	530
		A	2	530	230	760
		A	4	810	190	1000
	Idle				120	
Resource 2	Run	C	2	430	310	740
	Idle				760	
Resource 3	Run	B	1	100	100	200
		C	3	740	330	1070
	Idle				640	
Resource 4	Run	B	2	0	100	100
		A	3	760	50	810
	Idle				920	

The application of the formula for calculating SC gives the global values 4.989 bits for the level of detail I, and 2.93 bits for the level of detail II. SC does not provide, however, any indication on the number of times and the specific durations that a resource has been in a given state for a given time period. This example illustrates the fact that SDMC complements SC when assessing a manufacturing system.

For the level of detail I, the highest structural complexity per resource is associated with Resource 1 (2.121 bits). This reflects the variety associated with the number of jobs to be run on this resource, and with their associated time lengths. If we consider that the complexity associated with a *Run* state is by default higher than the complexity associate with the *Idle* state for the same duration, then we must also analyse the total complexity associated with the *Run* state for each machine and for all the resources. This analysis shows that for the level of detail I the SC values associated with the *Idle* state are comparable for all the resources, so the focus in the analysis and comparison phases should be placed on the *Run* state. An important remark on the interpretation of the SC values is that a hierarchical analysis of their components, in terms of types and values, is necessary in order to obtain an accurate picture of the system. A similar analysis can be performed for investigating the effect of each product on SC, as presented in Table 5.25. A valuable result that the structural complexity-based analysis shows is that Product A and Product B are of similar structural complexity levels.

Table 5.24 The probabilities and SC values associated with the schedule in Table 5.23

Resource	Job			Probability (I)	SC (I)	Probability (II)	SC (II)
	State	Product	Operation				
Resource 1	Run	C	4	0.402	0.529	0.887	0.152
		A	1	0.093	0.320		
		A	2	0.215	0.477		
		A	4	0.178	0.443		
	Run-State SC Resource 1				1.768		0.152
	Idle			0.112	0.354	0.112	0.354
	Total SC Resource 1				2.121		0.506
Resource 2	Run	C	2	0.290	0.518	0.290	0.518
	Run-State SC Resource 2				0.518		0.518
	Idle			0.710	0.351	0.710	0.351
	Total SC Resource 2				0.868		0.868
Resource 3	Run	B	1	0.093	0.320	0.401	0.528
		C	3	0.308	0.523		
	Run-State SC Resource 3				0.843		0.528
	Idle			0.598	0.443	0.598	0.443
	Total SC Resource 3				1.286		0.972
Resource 4	Run	B	2	0.093	0.320	0.140	0.397
		A	3	0.047	0.207		
	Run-State SC Resource 4				0.527		0.397
	Idle			0.860	0.187	0.860	0.187
	Total SC Resource 4				0.713		0.584
	Total SC				4.989		2.93

Table 5.25 The product-based analysis of Structural Complexity

Product	Resource	Operation	SC
A	1	1	0.320
		2	0.477
		4	0.443
	4	3	0.207
	SC Product A		1.447
B	3	1	0.320
	4	2	0.207
	SC Product B		0.527
C	1	4	0.529
	2	2	0.518
	3	3	0.523
	SC Product C		1.570

5.2.4 Computation of operational complexity

As presented in Section 4.4.2, prior to any OC assessment exercise, a problem needs to be identified. The problem that will be addressed in this example consists of assessing the OC of the material flow. The complexity of the material flow refers to time- or quantity-based deviations from the schedule, when completing one or more operations for all the scheduled products. Very important is the fact that this can be further interpreted and used as a measure of customer satisfaction.

Therefore, both time and quantity variations between actual and expected behaviour may be considered when investigating the material flow complexity. If a choice on which of them to investigate needs to be made, the decision should be made depending on what is perceived as the critical issue by the company, and on data availability. In order to calculate the time-based OC, information on the actual start and completion time of each operation of a product needs to be obtained. This data can be obtained either by researchers monitoring the system for the investigated period, or from the records on the system behaviour (the latter option assumes that the information recorded is accurate and reliable). The required data for the exemplified system and the identified problem are given in Table 5.26.

Table 5.26 The data for the time-based complexity analysis of the material flow

Prod.	Op.	Expected Start Time	Actual Start Time	Expected–Actual Start Time	Expected Completion Time	Actual Completion Time	Expected–Actual Completion Time	Reason
A	1	430	500	-70	530	600	-70	Resource 1 Breakdown
A	2	530	600	-70	760	830	-70	Resource 1 Breakdown
A	3	760	830	-70	810	880	-70	Resource 1 Breakdown
A	4	810	880	-70	1000	1070	-70	Resource 1 Breakdown, Non-Critical Path
B	1	100	160	-60	200	320	-120	More material, over-producing
B	2	0	0	0	100	160	-60	More material, over-producing
C	2	430	500	-70	740	810	-70	Resource 1 Breakdown
C	3	740	810	-70	1070	1170	-100	Resource 1 & 3 Breakdown, Critical Path
C	4	0	0	0	430	500	-70	Resource 1 Breakdown

The values in Table 5.26 show that the delay due to Resource 1 being in a *Breakdown* state for 70 time units is propagated through the system, and it generates several deviations from the expected completion time. The most critical delay is that of operation 3 of Product C, as it extends the actual production time from 1070 to 1170. This delay is due to the earlier breakdown of Resource 1, and to the breakdown of Resource 3 whilst processing this job.

Table 5.27 The state definitions and OC for material flow time-based variation state definition

State Definition	Boundary		Expected–Actual Start Time			Expected–Actual Completion Time		
	LB	UB	Occ.	Probab.	OC	Occ.	Probab.	OC
In Control	0	0	2	0.222	0.482	0	0	0
Out of Control 1	–1	–50	0	0	0	0	0	0
Out of Control 2	–50	–74	7	0.778	0.282	7	0.778	0.282
Out of Control 3	–75	–99	0	0	0	0	0	0
Out of Control 4	–100	–124	0	0	0	2	0.222	0.482
Out of Control 5	Other		0			0		
Total OC (Equation 4.3)					0.764			0.764
PlogP (Equation 4.3)					0.482			0
(1–*P*)Log(1–*P*) (Equation 4.3)					0.282			0
$(1-P)\sum_{i=1}^{M}\sum_{j\in NS} p_{ij}\log p_{ij}$ (Equation 4.3)					N/A, a single non-scheduled state			0.764

The state definition and the time-based complexity calculations for the material flow are presented in Table 5.27. The meaning of the *In Control* and *Out of Control* states in Table 5.27 has been defined in Section 4.4.1. In Table 5.27, LB represents the state's lower bound; UB the upper bound; Occ. the number of occurrences for a given state. A single *In Control* and five *Out of Control* states are defined. More details on the implications of using various methods for defining the states on the results are included in [SECH01b, Siv01]. In the current example, as an identical number of OC states, and identical lower (LB) and upper bounds (UB) have been used for both investigated flows, the results are comparable.

The data in Table 5.27 show that the total OC associated with variations between Expected and Actual Start Time is 0.764, and is equal to the total OC associated with variations between Expected and Actual Completion Time.

The analysis of the structure of the two OC values shows that:

1. The biggest contribution to the OC associated with variations between Expected and Actual Start Time is due to the system being *In Control*.
2. For the OC associated with variations between Expected and Actual Completion Time the system is never *In Control*, that is, the expected completion time and the actual completion time are always different.

OC values have been calculated by considering that, despite the deviations from the schedule, no rescheduling is made during the OC measurement stage (therefore there is no on-line SDMC).

5.2.5 A joint analysis of the insights provided by SDMC, SC and OC

The value of the total OC is significantly lower than both SDMC and SC. This shows that, for the exemplified system, the most difficult task is to create the schedule from the product specification and customer demands. This interpretation is confirmed by the value of the SDMC, i.e. 7.412 bits. Furthermore, the example considered in this section has shown that, for a given system, the SC is lower than SDMC.

The product-based analysis shows that the product with the highest SDMC and SC is Product A, followed by Product C and Product B (Table 5.21 and Table 5.25, Scenario I). The resource-based analysis shows that resources 1 and 2 have comparable SDMC values. They are followed by resources 3 and 4 (Table 5.21). For the resource-based analysis of SC, Resource 1 has the highest SC, being followed by resources 3, 2 and 4, respectively. At the operational stage, the reason-based analysis (Table 5.26) of the deviations from the expected behaviour indicates Resource 1 as the critical component. A possible direction for action would be to improve the reliability of Resource 1 – especially if a further analysis, possibly based on historical data, reveals that Resource 1 exhibits recurrent Breakdowns. Another possibility would be to schedule on Resource 1 only the tasks that have no other alternative, such as Operation 4 of Product A, or Operation 4 of

Product C. It is predicted that this action would reduce the SDMC, as the operation and resource flexibility would decrease. The SC would also decrease, with resources 2, 3 and 4 being able to use the idle time for processing. Furthermore, OC would decrease as well, as the system will deviate less from the schedule. This prediction is based on the assumption that the resource capacity would be able to cover the demand, that no other resources will break down, and that the demand would not change.

The next section briefly considers the results presented in Chapter 3 from an information-theoretic perspective.

5.3 The analysis of the kanban system in Chapter 3 from an information-theoretic perspective

In this section we revisit the kanban system modelled in Chapter 3, and investigate the applicability of the complexity measurement framework presented in Chapter 4 for the detection and diagnosis of critical issues.

As presented in Section 3.2, all the machines in the system produce the same type of product, therefore there is no SDMC associated with this system. Similarly, the machines are expected to produce as much as and when required, at the expected throughput rate. As the machines and the number of kanbans between them are identical, the structural complexity of the system is given by the structural complexity of any machine. Therefore, their associated SC could be either zero, if the machines are expected to produce continuously, or a value less or equal to one, otherwise. This is due to the fact that there are at most two possible states at each machine, *Run* and *Idle*.

Hence, the only source of complexity in the system is the operational complexity due to variable processing times. Let us assume that the problem to be investigated is the variability of the throughput rate, and the aim of the investigation is to identify the optimum system configuration for the current throughput rate. The throughput rate has been monitored for all the combinations $1 \leq No\_kanbans \leq 5$ and $1 \leq Lot\_size \leq 5$.

The information-theoretic approach to this problem is to identify the critical states for the system, i.e. the *In Control* and *Out of Control* states. If we assume that the system is monitored every 10000 time units, and therefore the expected throughput when the machines are expected to work continuously is 10000, then a possible set of states would be as defined in Table 5.28. The *In Control* state allows a variation of less than 100 from the expected quantity. Any variation higher than 100 will represent an *Out of Control* state. The severity of the variation will identify the state, through its associated Lower (LB) and Upper (UB) bounds.

Table 5.28 Quantity-based state definition for the kanban system in Figure 3.2

State definition	LB	UB
In Control	0	100
Out of Control 1	100	500
Out of Control 2	500	1000
Out of Control 3	1000	2000
Out of Control 4	2000	4000
Out of Control 5	4000	Not defined

A set of measurement data has been generated by considering that for each configuration (*Lot_size, No_kanbans*) 11 different values of throughput have been observed, each of them corresponding to the different coefficients of variation (*CV*) considered in Figure 3.2. Therefore, the system observed is highly unpredictable, as the observed value of the throughput varies significantly from one measurement to another. An important remark is that the theoretical *CV* corresponding to a real process is often unknown, especially in highly variable systems as the one considered in the current example. The LB and UB for each state might vary with the desired level of control in the system. These tolerance levels refer to the difference between the expected

(10000) and the actual level of throughput. In the example considered in Table 5.28, the tolerance level for the *In Control* state is quite low, as the expected reliability and predictability of a kanban system is relatively high.

For the data thus obtained, we have calculated the OC using the state definitions in Table 5.28, and the results are presented in Figure 5.1. The optimal system configuration would ideally have an *In Control* component and a reasonable value of the *Out of Control* Complexity. According to the results presented in Figure 5.1, two possible configurations that fulfil these conditions are (*No_kanbans*, *Lot_size*)=(2, 4) or (*No_kanbans*, *Lot_size*)=(4,2). These results coincide with the configurations discussed in Section 3.5. Most important, the analysis in Section 3.5 can be read either as a continuation or as an introduction to this section.

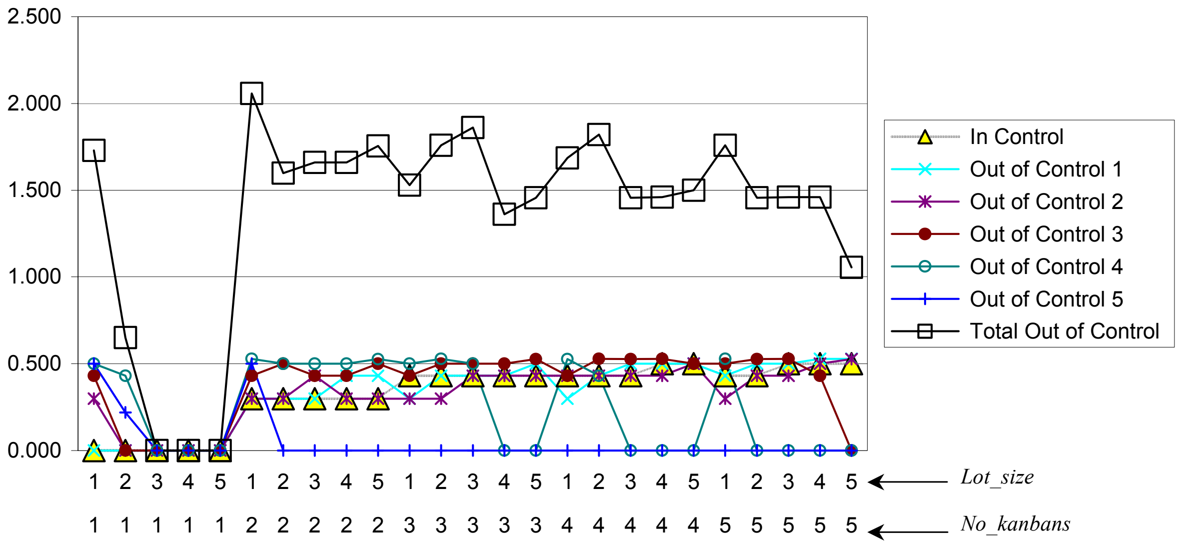

Figure 5.1 The state-based structure of OC for different system configurations and identical levels of variability

For example, the configuration (*No_kanbans*, *Lot_size*)=(5, 5) would yield a lower *Out of Control* OC and a similar *In Control* OC as those corresponding to (*No_kanbans*, *Lot_size*)=(2, 4) or (4, 2). A critical concern about this configuration is, however, the increase in the volumes of WIP allowed into the system. A similar thread of reasoning has been followed in Section 3.5, but was initiated by a modelling and simulation approach.

The limitations of the configurations (*Lot_size, No_kanbans*,) = $(3,1)$, $(4,1)$ and $(5,1)$ have also been captured by the complexity measurement framework. For these configurations, both *In Control* and *Out of Control* elements of the OC are zero. This is explained by the fact that there is no *In Control* state and only one *Out of Control* state.

5.4 Summary

This chapter has demonstrated the application of the manufacturing complexity framework presented in Chapter 4 for the calculation, analysis and interpretation of SDMC, SC and OC, both individually and jointly.

In Section 5.1, the manner in which SDMC is calculated has been illustrated and the results interpreted for various classes of systems. The specialised (operation-, resource- or batch-based) analysis of SDMC has proved of significant value in providing useful insights on the various contributors to the total SDMC, and on the potential directions of improvement of product and process design. The SDMC represents the amount of information required to create a schedule, and is therefore linked to the difficulty of scheduling-related decisions associated with a given system configuration. The analysis of the structure of the SDMC indicates the contribution of various elements such as product, resources and precedence relationship on the total index. The SDMC framework established an analytical means for integrating various systemic characteristics in a measure that, together with the SC and OC, can be used to support design and control decisions.

Section 5.2 has exemplified the individual and joint application of the SDMC, SC and OC for a theoretical system. The analysis performed revealed the interactions between classes of complexity, and their individual potential to identify and assess structural and operational criticalities.

The final section of the chapter, Section 5.3, has considered the example in Chapter 3, and has reached results similar with those in Chapter 3 by using the information-theoretic approach presented in this thesis.

6 Identifying, analysing and assessing manufacturing complexity

Mens et Manus (Mind and Hand)
The MIT Motto [MIT]

Reality is just a convenient measure of complexity.
Alvy Ray Smith [Smi]

In this chapter we apply in practice the concepts presented in the previous chapters of the thesis. The objectives of this chapter are:

- To present the methodology for measuring manufacturing complexity and discuss the practical aspects involved in measuring complexity (addresses the measurement methodology component of question 3 in Section 1.2).
- To summarize several case studies in which individual information-theoretic measures of complexity where used to identify and assess problems (questions 8 and 9 in Section 1.2).
- To illustrate the applicability of the theoretical framework presented in Chapter 4 in a real case study (questions 1, 3-9 in Section 1.2).
- To illustrate how the manufacturing complexity framework provides an increased level of objective, qualitative and quantitative understanding of manufacturing complexity, and of the relationship between a system's complexity and its performance in a specific case study (questions 1 and 3-9 in Section 1.2).

In Section 6.1 we present the methodology for identifying, analysing and measuring the various aspects of manufacturing complexity presented in Chapter 4. Section 6.2 summarizes several case studies, with a focus on the type of industry, the objectives followed, and on the benefits obtained and lessons learned, by both academic and industrial sides. A detailed presentation of the application of the complexity framework presented in Chapter 4 to a case study is presented in the remaining sections of the chapter. Sections 6.3 and 6.4 present the case study domain and the issues detected in the investigated facility. Section 6.5 illustrates the manner in which SDMC, SC and OC are used to identify and assess critical issues in a real complex case study. Section 6.6 discusses the results obtained by applying the complexity framework, and Section 0 summarises and concludes the chapter.

The results in Sections 6.1 to 6.4 represent joint work with colleagues within the Oxford Manufacturing Systems Group, and have been published in journal and conference papers and as reports submitted to the industrial collaborators ([Cal97a, Cal97c, CESB98, CES+00, ECS+01, SEF+02, SECH02, SHZ+00]). The cases summarised in Section 6.2, and the case study presented in detail in Sections 6.3 to 6.6 have been used at various stages of the research reported in this thesis, for the purposes of: exploration, theory building, theory testing and theory refinement [VTF02, Yin94].

6.1 Fieldwork methodology and practical issues

The theoretical framework on the development of measures of SDMC, SC and OC has been extended into a methodology for measuring the complexity of manufacturing systems and of supply chains, which has been applied and validated through case studies ([Cal97a, Cal97c, CESB98, CES+00, ECS+01, SECH02, SEF+02, SHZ+00]). This section will briefly present the measurement methodology.

The key feature of fieldwork is the opportunity to observe real manufacturing processes. This is an effective way of taking researchers beyond the theory and into practical applications [VTF02]. In manufacturing research, real-life industrial exposure develops an understanding of the links between manufacturing systems, information and human systems. Access to industrial partners is often the prime barrier to many academics wishing to conduct case study research. The chances of industrial partnership depend largely on the strength of the project proposal in terms of benefits (‘*what’s in it for us*?’) for the company. The other influential factor is the *project champion,* the right person within the company who can take industrial ownership of the project and drive it forward. Access to the right people, at all necessary levels, is critical.

Selecting the right combination of research tools can also be critical to the quality, quantity and ease of data collection and evaluation. Case study researchers have an extensive range of approaches to choose from, depending on the particular type of investigation and organisation targeted [Yin94]. A toolbox of methods can be adopted and arranged to suit the investigation at hand. Once the appropriate techniques have been selected, meticulous planning of the research process is required on both macro and micro level. The on-site time available to researchers for access to personnel and measurements is often limited due to the constraints of the industrial partners. This fact, combined with the relatively high research costs (time, personnel and money) of conducting fieldwork, emphasises the need to take a strategic approach in all details of the research: from planning, designing, and execution through to dissemination.

The proposed methodology requires the investigators to work closely with the industrial organisations, with two investigators typically spending up to three weeks on their premises, followed by a phase of data analysis and preparation of presentations. The schedule for applying the methodology consists of the five phases shown in Table 6.1, with their suggested duration.

Table 6.1 Phases in applying the complexity measurement methodology

Phase No.	Objectives	Duration
Phase 1	Familiarization	1 week
Phase 2	Preparation and initial presentation	1 week
Phase 3	Data acquisition	2 to 3 weeks
Phase 4	Data analysis and presentation	2 weeks
Phase 5	Final analysis and report writing	1 month

6.1.1 Familiarization

The first phase is carried out on the site of the collaborating organisation. The investigators map the flow of material and information, and money too, if possible, and if considered of value to the investigation. They identify the decision points in the flows and the key personnel involved in the activities of monitoring and scheduling. By talking to these people, they identify the main problems they face and the level of criticality they assign to them. The main documents that are used in the activities of monitoring, scheduling and reporting are identified, together with their origin and destination, and frequency of generation and update. Samples are taken of these documents. These samples are used to identify the formal and informal names of the documents at different points in the flow of material and information. The key points in the flows, where the states of the resources can be monitored, are identified, together with the set of relevant states for each resource.

The key deliverables of this phase are:

1. A description of the layout of the facility;
2. A description of the documents which are used to monitor and control the production process;
3. A description of the critical issues identified.

The first task is to identify all the documents that are used to communicate to, from, and within the scheduling function. The data items that occur in each document are logged, together with those that are or may be changed. The frequency of generation of the documents is determined, as well as the lifetime of the document and its frequency of update. A subsequent analysis of the documents compares the actual contents of the documents as they progress through the manufacturing process. This is used to calculate the complexity values in Phase 3. The main technique that we have used during the mapping of the document flow is the IDEF approach [Ber97, Cal97c, ECS$^+$01, ZZ96].

6.1.2 Preparation and initial presentation

The second phase is carried out back at the university. The outcomes of the first phase are written up and prepared for presentation to the company, in the forms of IDEF diagrams, maps and tables. Data acquisition forms are drafted. This usually takes about one week, but its length depends on the number of researchers available versus the accumulated volume of information. A formal written report is not prepared at this stage, due to the limited value it would have, but a 30-40 minute formal presentation is prepared, with a handout circulated to attendees. The proposed schedule of measurements is presented at this stage. This allows the industrial collaborators to understand and authorize access to the relevant personnel and resources over the required amount of time. It is important to obtain feedback from the collaborators at this stage to make sure that the flows and maps are correct and complete. It is also important to make sure that the flows that have been identified for investigation are agreed as being important and relevant to the perceived issues of the organization. One must also check that the proposed schedule of measurements is physically feasible. This presentation is usually given at the start of the third phase of data acquisition.

6.1.3 Data acquisition

The data acquisition phase is carried out by the investigators on the site of the participating organization and usually lasts between two and three weeks. Ideally, one would like to have longer in order to make sure that all possible states of the system are observed, but a manufacturing system is always subject to change and it would be stretching goodwill to spend much more than two or three weeks on site. This is a period of intensive activity, requiring the investigators to move around the facility monitoring the state of the resources at intervals related closely to the rate of change of state of the resources of interest. The data acquisition forms are used to enable the observations to be taken consistently and quickly. These may be on paper, but it assists with the later analysis phase if they can be prepared and completed directly on computer.

6.1.4 Data analysis and presentation

The fourth phase is completed back at the university. It is important that this phase too is completed promptly and on time, since the collaborating organization will quickly lose interest if the analysis and report are late. Also, the findings may go out of date due to the natural rate of change and shifting priorities of the organizations. During this phase, the main analyses calculate the probability of a resource being out of control and the dynamic complexity associated with that condition. The dynamic complexity is calculated with respect to a schedule, so it is often of interest to show how the performance of the system develops as the material flows through the system. This can be done with the flow of material and the flow of information. For example, a recent study performed as part of a case study followed the information and material flows at a supplier-customer interface. The requested delivery dates on the original purchase order were compared with those on the acceptance note, progress report, scheduled production and actual delivery. This analysis was able to show that the progress report contained so little new information that it was not worthwhile for one organization to generate it, and the other to process it [SHG+].

The findings at this stage are presented to the collaborators as a preliminary presentation, in order to provide feedback to them, and to validate the results. It usually turns out during this phase that the number of interesting results far exceeds the scheduled presentation time of about 40 minutes. A thorough analysis and selection of the results is required in order to identify the most interesting and surprising results, so that the presentation can be focussed on them. The findings that are not presented at this stage are, however, included in the final report. The results are presented as numerical values on the probability of a flow being in control and the calculated complexity, illustrated by pie charts and histograms.

The presentation of findings is followed by a period of discussion of between 30 and 60 minutes. The audience at the presentations consists of as many as possible of the personnel who were involved with the data acquisition, both on the shop floor and in the offices, plus the people directly responsible to suggesting and implementing organizational changes. These meetings are a valuable opportunity to discuss issues, based on measured, objective, data, and to confirm or refute feelings. Again, it is important to obtain feedback on the findings to see if they agree with the perceptions of the personnel who are familiar with operating the material and information processing systems under investigation. In most situations, the areas that turn out to be most complex, according to the complexity calculations, are those that the collaborators have found to be a problem too. Placing numerical values on these issues is often a real benefit in allowing them to set priorities and understand the complexity of the problems that one another have to deal with. The reason-based analysis is an important component of the analysis, as it bridges the gap between conventional and information-theoretic approaches to understanding a system's behaviour.

6.1.5 Final analysis and report writing

In this phase the company-specific results are presented and documented in a comprehensive report for each company. The feedback obtained in Phase 4 is also incorporated in the report [SHG+00, SHZ+00].

6.1.6 Remarks on methodology

Depending on the problem investigated, on the interest and commitment of the involved company or companies to the project, and on the evolution of the facility investigated, a re-run of the Phases 1 to 5 can be performed, with new problems related to those previously assessed being investigated. This allows a deeper level of analysis and systemic comparisons across different time intervals to be performed.

The complexity measurement task presupposes the involvement of different resources in different departments, people and machines. So, it is time-consuming; it also requires involvement, honesty and a genuine desire to learn and improve on the part of all involved in the project [RH97]. Indeed, in assessing manufacturing complexity care should be taken so that the observed system's behaviour is not significantly influenced by the observers' presence. This has been considered by carefully explaining the objectives, data requirements and the practicalities of the case study to all the people involved prior to taking the measurements. The familiarization phase also plays an important role at this stage in the identification of the appropriate points and frequency for data collection Furthermore, since much of the prerequisite information and data has to be provided by the people in the analysed facility, they must be prepared to openly and actively collaborate to the complexity assessment process. For this to happen, the methods and objectives involved in a complexity assessment project, and the expected benefits, must be well documented and explained to all the people involved.

The application of the framework requires a high degree of professionalism, co-operation, honesty, respect and responsibility from both parties: the people in the analysed facility, and the researcher(s).

6.2 Examples of case studies

Several case studies will be summarised in this section, in order to illustrate the applicability and utility of the complexity measures. The focus will be placed on:

- The type of industry;
- The objectives of the case study;
- The issues investigated;
- Meaning and benefits for industry;
- Lessons Learned (Academia).

The case studies are presented in the temporal order of their development.

6.2.1 The automotive industry

The facility investigated in this case study is in the automotive industry, and is presented in more detail in Sections 6.3 and 6.4. The objectives followed were to apply and assess Frizelle's method for measuring complexity [Fri95, Fri96].

The issues investigated include unreliable schedules, customer changes and high volumes of WIP.

Measurements were made on three consecutive day shifts, and on two night shifts. During the measurements the queue length and the state for all the machines in the system, and the dynamics of the WIP were recorded. Each measurement required 3 people and took between 30 and 40 minutes, according to the workload level.

Only the Operational Complexity was calculated, as Frizelle's method considers that Structural Complexity should be calculated for very long periods (usually a year).

The practical insights and benefits obtained include:

- The unplanned OC associated with the queue contribution is low if OC is calculated per resource type rather than per individual resource;
- The In Control component of OC contributes significantly to the overall complexity. This indicates a high SC;
- The OC takes low values, due to the short-term scheduling and the shop-floor procedures used;
- The unplanned OC is highest for the most heavily loaded group of machines (confirmed as bottlenecks by the shop's managers).

The lessons learned include:

- The need for a unified framework for measuring manufacturing complexity;

- The entropic methods provide objective measures of complexity, dependent on the state definitions;
- The measurement duration and cost depends on the size of the analysed facility and on the number of types of products produced;
- The entropic measures have high measurement costs;
- The results obtained are cryptic, their meaning is open to and dependent of interpretation;
- Measuring only material flow is not sufficient. The reason-based analysis of the structure of OC did not indicate the impact of customer changes on the OC. This is explained by the fact that the measurements were focussed on material flows and resource states, and did not consider the deviations from the schedule and their reason.
- The Short Term scheduling, and the lack of appropriate information on the WIP area hides the actual WIP complexity in the system.
- SDMC is not captured by existing methods. Therefore, the methodology had to be adapted so as to cope with short-term scheduling in the analysed facility.

The results of this work have been published in [Cal97a, Cal97c, CBES97, CEBS97a, CEBS97b, CEBS97c, CESB98]. Furthermore, these results and insights have been used in the development of the manufacturing complexity framework presented in Chapter 4. The data collected has also been used for testing the SDMC measure, and for the joint SC, OC and SDMC analysis in Sections 6.3 to 6.6.

6.2.2 The aeronautic industry (I)

The facility investigated in this case study is in the aeronautic industry, and is characterized by high precision machines, and by complex products with a high emphasis on quality. The objective was also to adapt, apply and assess Frizelle's methods for measuring complexity, i.e. theory and methodology testing [Fri95, Fri96].

The issues investigated include unreliable schedules, difficult to predict work rates, equipment breakdown and faulty products, and customer changes. Measurements were made at 30 minutes intervals for three consecutive days. During the measurements the queue length and the state for all the machines in the system, and the dynamics of the WIP were recorded.

The practical insights and benefits obtained include:

- The sources of complexity identified were the existing policies on dealing with customer changes in product and design demand.

The lessons learned include:

- The OC is less than the SC for all the work centres. However, due to practical reasons, only the work in front of a machine was measured leading to the real queue being ignored. Therefore, the validity of this result is limited The fact that the limiting resource is the workforce and not the work centres was not captured by the measurements.
- Frizelle's method could not detect the sources of manufacturing complexity, as it concentrates on shop-floor processes rather than on the disturbances affecting the schedules.
- The advances in the methodology presented in Chapter 4 overcome these limitations. Greater insight on the facility has been obtained by applying the novel complexity measurement methodology presented in this thesis.

These conclusions have confirmed the results in Section 6.2.1, and have been taken into account when developing the framework presented in Chapter 4.

6.2.3 The aeronautic industry (II)

In this case study, the objective was to measure the Operational Complexity at the interface between the company presented in Section 6.2.2. and one of its suppliers [ETS+99, SHG+00, SEF+02]. In this case, as presented in Chapter 4, the state definitions and measurement were based on variations in information flows in the scheduling documents.

The issues investigated include unreliable schedules, difficult to predict work rates, equipment breakdown and faulty products, and customer changes.

One week was spent for the familiarization phase, and the measurements were made twice daily for two weeks. During the measurements the variations in information for the scheduling documents were recorded.

The practical insights and benefits obtained in this case study include:

- Poor scheduling is due to information incompleteness and inconsistency (three different scheduling documents), short-notice changes to the schedule, and to the lack of detailed information of the shop floor's processing capability.
- The internal customers export OC to the investigated facility, which has to cope with (absorb) it.
- The investigated facility exports complexity to its supplier through customer changes.
- The supplier exports complexity to the investigated facility through poor quality products and incomplete deliveries.
- Incompatible Information Systems account for a high OC at the interface.
- The supplier charges the investigated facility for dealing with high levels of complexity it generates.

The lessons learned include:

- The granularity of information-based state definition had to be determined by observing the system in the familiarization phase, and by consulting with the production managers and schedulers at the both sides of the interface, in order to establish the granularity level corresponding to each level of criticality.

This case-study tested the theoretical method for measuring operational complexity in Section 4.4 and emphasised the importance of information, both internally and at the interface. This method was further extended to formalize and measure the operational complexity of supplier-customer systems [SECH01a, SECH01b, Siv01].

6.3 Application of the manufacturing complexity framework: The case study domain

The facility investigated is a low-technology process-based job-shop within a major automotive UK manufacturer, which accommodates a high number and type of tool-based machines. The main features of the analysed facility are:

1. A high number (65) and type (9) of tool-based machines, arranged in a job shop (process-based) layout;
2. The system manufactures a high number of products (around 1000), most of them requiring several operations (between 1-8), often on machines of different types, in a wide variety of batch sizes. This requires frequent machine changeovers, the effect of which on the system performance is amplified by the significant changeover times when compared to processing times;
3. The "theoretical" cycle time is between 4 and 6 weeks. Practically, jobs are often interrupted once enough has been produced to satisfy the short-term demand, in order to set and run urgent jobs. There are also jobs which re-appear on the plan twice or three times a month;
4. No home lines, i.e. only the type of machine required by an operation is specified in the planning phase. The operation may be performed on any machine of the required type, this decision being made in the scheduling phase;
5. Multi-skilled workforce; for any operation (machine set-up, run and repair, and part movement), an operator is necessary;
6. Fewer operators than the number of machines.

7. The shop planning is MRP–based and done on a weekly basis. The scheduling is manual and shift-based, and consists of assigning the jobs to specific machines, so that they are completed before the due date. The schedule therefore contains only sequencing and routing information. The information on a job is manually updated on the computer at the end of each shift only if a change in its status took place. Several documents are used for planning and scheduling. No computer support is used for scheduling and decision-making at the shop-floor level. Scheduling is in fact only job routing and sequencing. Two documents are manually generated by the shop planner on a shift-by-shift basis. The first one is the Priority document, which specifies the jobs priorities. The second one is the Status document, which contains detailed information about the status of each machine (such as Idle, Waiting Changeover, Running, No Operator), the job currently assigned to it, the date the job was set, and follow-on jobs. Samples of these documents and an IDEF diagram depicting the scheduling documents and steps are included in [ECS+01]. In creating these documents the planner uses the MRP plan, his own expertise, the current-shift documents and shop-floor information about the current status of jobs and machines. Changes in the plan due to various reasons such as customer changes, data inaccuracy, quality problems or human errors are usually taken into account by the scheduler, they disrupting the current plan and schedule.

All these static and dynamic characteristics reflect high opportunities for flexibility, but also high degrees of freedom in planning and production, which need to be properly exercised and controlled. These characteristics give an insight into the high level of flexibility and complexity associated with the scheduling process. Once a job is set, however, running it is a simple and reliable process. The faulty parts are mainly due to machine or tool breakdown.

6.4 Application of the manufacturing complexity framework: Problems detected in the analysed facility

The problems identified in the analysed facility include failures in satisfying the plan, large volumes of WIP, and customer changes. The system's ability to cope with these problems is further reduced by high absenteeism. These features are specific to the investigated shop floor in the plant. Moreover, it is worthwhile and fair to mention that the system in the wide sense works. Different solutions have been adopted in order to solve these problems, such as running partial jobs or defining local criteria for scheduling, i.e. interpreting the plan in a personal manner. Although these solutions temporarily satisfy the customer, they do not solve the problems in-depth. The following issues have been identified in the facility:

1. Changes in customer requirements (in terms of new order, order size, specification or due date) taken in consideration; internal customers are the main sources of changes;
2. Reactive short-term scheduling;
3. Poor plan stability and schedule adherence;
4. Poor computer support for schedulers;
5. Large amounts of WIP, poorly monitored and controlled; the WIP area contains jobs which are on hold or static for long periods, or jobs which were interrupted before being completed ;
6. The shop-floor management considers the workforce is the limiting resource;
7. High absenteeism;
8. Information problems – in terms of information flow, quality, timeliness and accuracy of data, and non-value adding information-processing operations;
9. Poor inter-departmental communication; decisions made at management level or higher not always discussed and/or explained;
10. Lack of consensus on the business objectives between shop floor managers and top management;
11. Frequently pulling jobs short once enough has been produced to satisfy the short-term demand, in order to run urgent jobs;

12. Quality problems, due to machine or die breakdowns;
13. The performance measures in use (such as Overall Equipment Efficiency and schedule adherence) do not capture the problems and do not reflect their causes.

6.5 Application of the manufacturing complexity framework: Manufacturing complexity in the analysed facility

The SDMC, SC and OC have been assessed for a week (five days) worth of data, considering a scheduling horizon of two shifts totalling 17.25 hours (8 hours per day shift and 9.25 hours per night shift) for Monday to Thursday, and of 5 hours for Friday.

The computation of the SDMC was based on the following information:

- The plan: the products and their lot sizes;
- Product description and type of machines required;
- Machine description, classes of machines, and the number of machines in each class;
- Product-specific set-up time and processing times;
- Operations requiring multiple resources.

The following information was necessary for calculating SC:

- The plan;
- The types of resources required by each operation.

This information was obtained by mapping the plan to the operational requirements of the products. This information was collected in two ways. First, a team of researchers observed the system for a shift and recorded information on the basis of the actual system behaviour, through product specific cards. This information was then correlated with the information in the Priority, Status and Overall Equipment Efficiency documents. These documents were then used to obtain data on the remainder of the week. When there was a mismatch between these documents, further clarification was requested from the schedulers, team leaders or operators, as needed.

This method is correct because the type of operation flexibility embedded in the system only refers to identical resources (i.e. an operation that may be performed on more than one resource would require the same set-up and processing time on all of them). Therefore, the probability of a specific type of resource being in a specific state was calculated, rather than calculating the resource-specific probability.

OC was calculated based on the following information:

- The Overall Equipment Efficiency document, which is a document used for reporting on the system's performance; this document is updated regularly during each shift. The precision aimed for filling in the information in this document is 30 minutes. The number of data items recorded and analysed for each machine was 148 = (17.25*2*4+5*2). In the first term of the sum, 17.25 represents number of hours per day, 2 indicates that measurements were taken twice per hour, and four indicates the number of days (Monday to Thursday). The last term corresponds to the measurements taken on Friday.
- The 30-minute measurement interval ensures that no significant state of the system is missed, and has been obtained from the familiarisation phase and from direct observations of the system [CESB98, ECS+01].

6.5.1 How things should happen

The title of this section indicates that the results presented here are based on the information in the plan and in the schedule. Therefore, they are related to the system's expected behaviour. The SDMC and SC are calculated and the results interpreted.

6.5.1.1 Scheduling-related decision-making complexity

As each machine has to be set up to run a new product, the set-up times have been included in the processing time. Therefore no set-up precedence constraints have been included in the SDMC model. The results in Table 6.2 show that, although the number of jobs to be scheduled on Friday is significantly smaller than the number for Monday to Thursday, the difficulty of making decisions, determined by the volume and structure of information relative to the corresponding scheduling horizon, has similar values for all five days.

Table 6.2 The day-specific SDMC values

Day	Number of parts	Number of SDMC-contributing factors	SDMC
Monday	24	487821	18.507
Tuesday	25	758030	19.101
Wednesday	19	380767	17.879
Thursday	18	285945	17.595
Friday	12	165535	16.991

Table 6.3 specifies the number and types of resources in the system, and the type of operations they can perform.

Table 6.3 Resource set specification

Machine Type	Number of machines
Shear Squares	2
Blanking I	2
Blanking II	7
Blanking III	3
Blanking IV	3
Forming II	13
Forming III	12
Forming IV	17
Forming V	6

In Table 6.3, indices II to IV refer to similar types of resources used for different types of operations (i.e. Blanking II to IV and Forming II to IV respectively). This characteristic has no immediate impact in the operational stage. However, it is worth mentioning it due to the potential it offers for system re-design.

If we analyse the contribution of each of the resource classes to the total SDMC values, the SDMC value is the highest for the Forming II, III and IV types of machines (Figure 6.1). The SDMC is actually distributed between these three classes of machines. From the scheduler's point of view, the most demanding tasks are related to the Forming II, III and IV resources. The data in Table 6.3 show that these three classes have the highest number of resources. Intuitively, the higher the number of machines that can perform an operation, the higher the flexibility associated with that operation; therefore, the results in Figure 6.1 might not seem surprising.

The contribution of Figure 6.1 consists of the fact that it shows how the actual product demand is mapped onto each resource class, and how it impacts the structure of SDMC. For instance the SDMC values corresponding to the Forming II and III machines in Figure 6.1 are different, although the number of resources in these classes are very close. This shows that the level of demand on the Forming II class of resources is lower than the demand corresponding to Forming III machines.

Variations in the absolute values of SDMC, from one day to another, within a type of resources, correspond to variations in the volume and structure of the product demand. No jobs were scheduled on the Blanking I resources during the investigated period.

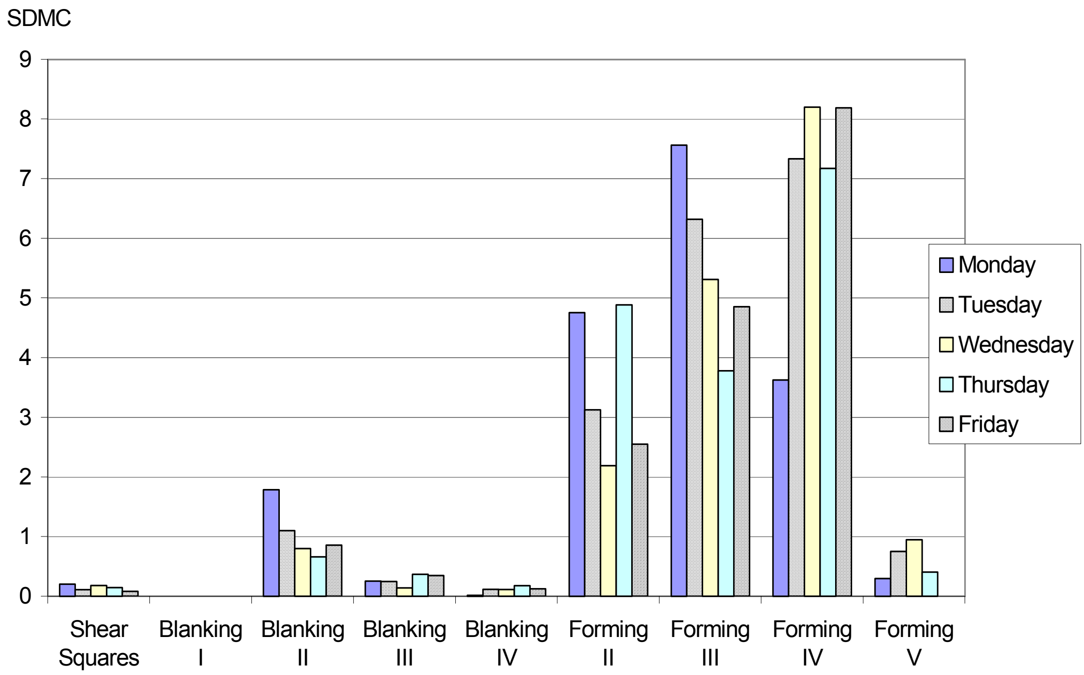

Figure 6.1 Resource type-specific SDMC

The results presented in this section illustrate the ability of the SDMC method to integrate various features within a complex manufacturing system, and to generate comparable results at the entity, entity class or system levels.

6.5.1.2 Structural complexity

For the investigated system, SC has been calculated for three classes of states: *Make*, *Set-up* and *Idle*, using the formula in Equation 4.2. The global and resource type-specific daily SC are presented in Table 6.4 and Figure 6.2, respectively. These results show that the highest SC is associated with Tuesday, and the lowest with Friday. The SC values for Tuesday, Wednesday and Thursday are close together.

Table 6.4 The day-specific SC

Day	Number of parts	SC (bits)
Monday	24	6.26
Tuesday	25	8.97
Wednesday	19	8.12
Thursday	18	8.88
Friday	12	4.64

Furthermore, the chart in Figure 6.2 indicates that most of the resource type-specific SC values are high on Tuesday and Thursday, with more dispersed values for the rest of the days.

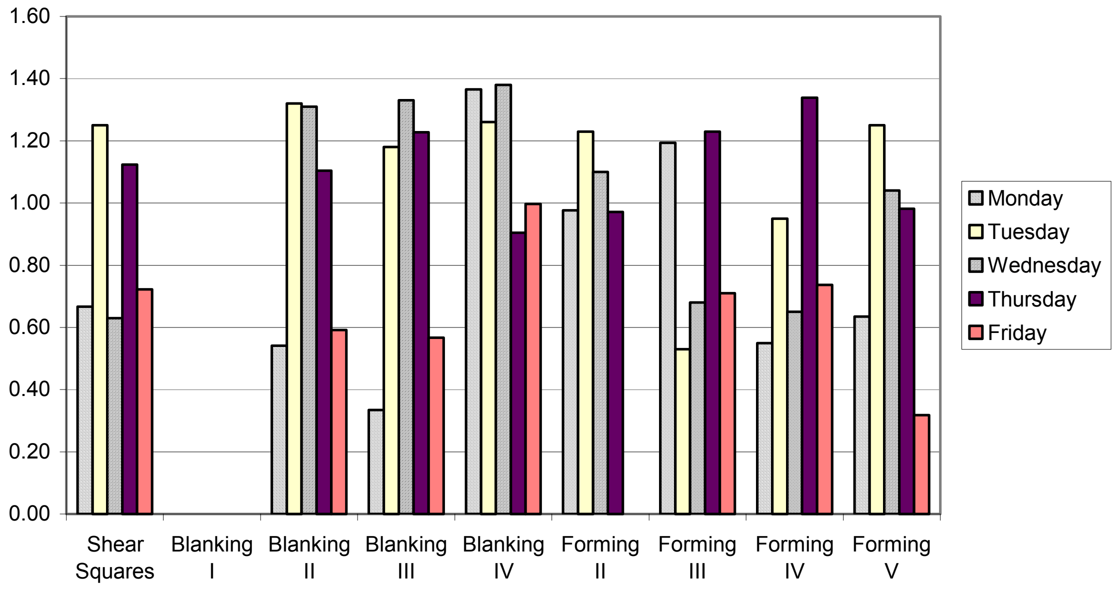

Figure 6.2 Resource type-specific SC (Equation 4.1)

The comparative state-based analysis of the constituents of SC (Figure 6.3) shows the variation of the SC associated with the *Set-up* and *Make* states throughout the week. Notice for example that the highest values of SC for all three types of states are obtained for Thursday. Furthermore, the SC corresponding to the *Idle* State for Friday is null, indicating that no resource is planned *Idle* on that day. This is confirmed by the results in Figure 6.5 and Figure 6.6, which indicate that on

Friday all the resources are planned to occupy either state *Make* or *Set-up*. The SC associated to the Idle state increases from Monday to Thursday, and is 0 for Friday. This planned behaviour is also accompanied by having on Friday the highest *Set-up* SC in the week, due to planned frequent job changeovers (Figure 6.3). Furthermore, the analysis of the collected data showed that the jobs scheduled for Friday exceeded the actual capacity for all the types of machines in the system. Therefore, the SC analysis identified poor scheduling techniques, and unfeasible and imbalanced schedules.

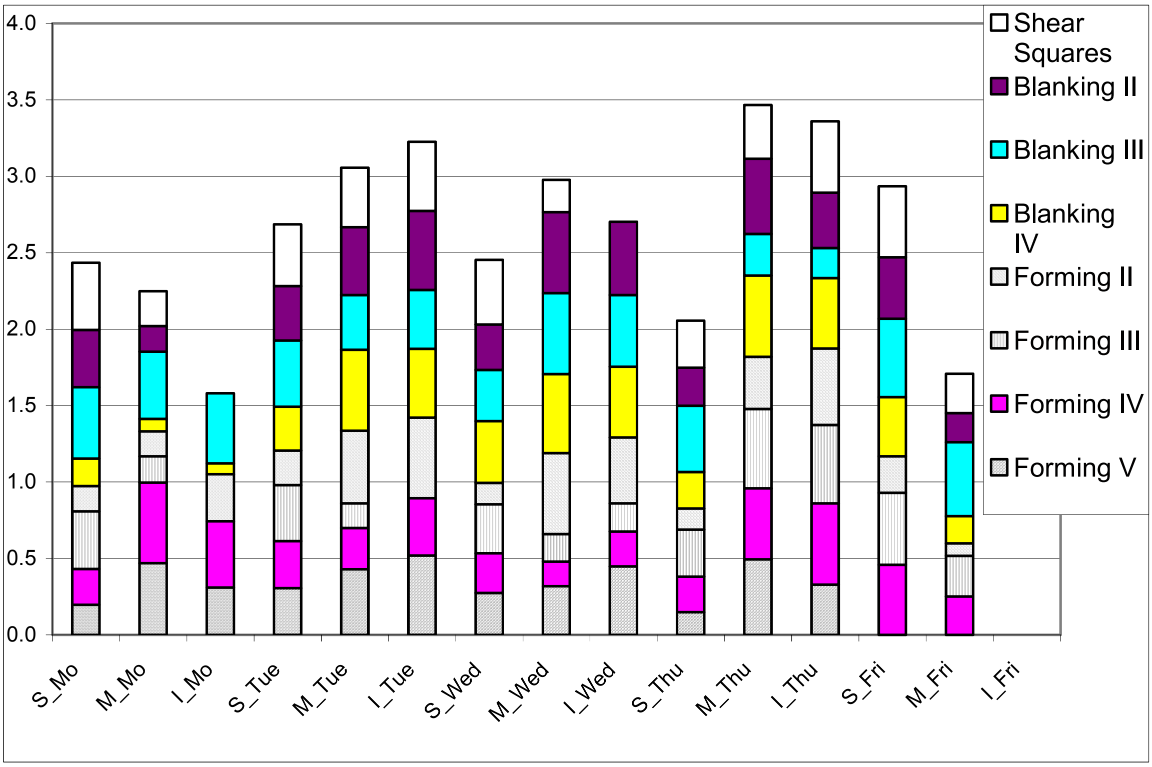

Figure 6.3 A comparative analysis of the constituents of SC calculated per resource type, for three classes of states: S=*Set-up*, M=*Make*, I=*Idle*

The results in Figure 6.3 have been obtained within the assumption of independent states and resources, which allowed SC for similar states at different resources to be summed up together and compared. In Figure 6.4 a cumulative chart of the planned average % time per resource-type for the states *Set* or *Make*. The individual percentages per resource type for the *Make* and *Set* states have been represented for clarity in Figure 6.5 and Figure 6.6. A comparative analysis of the results in Figure 6.3 and Figure 6.4 indicate that a policy of maximising throughput and reducing the number of set-ups is not necessarily optimal from the information-theoretic perspective. Indeed, the relative difference between the SC values corresponding to the *Set* and *Make* states is significantly smaller than the relative difference corresponding to the average planned time in the *Set* and *Make* states. Therefore, the average measures of resource utilisation and set-up do not accurately reflect the amount of information required to control the system.

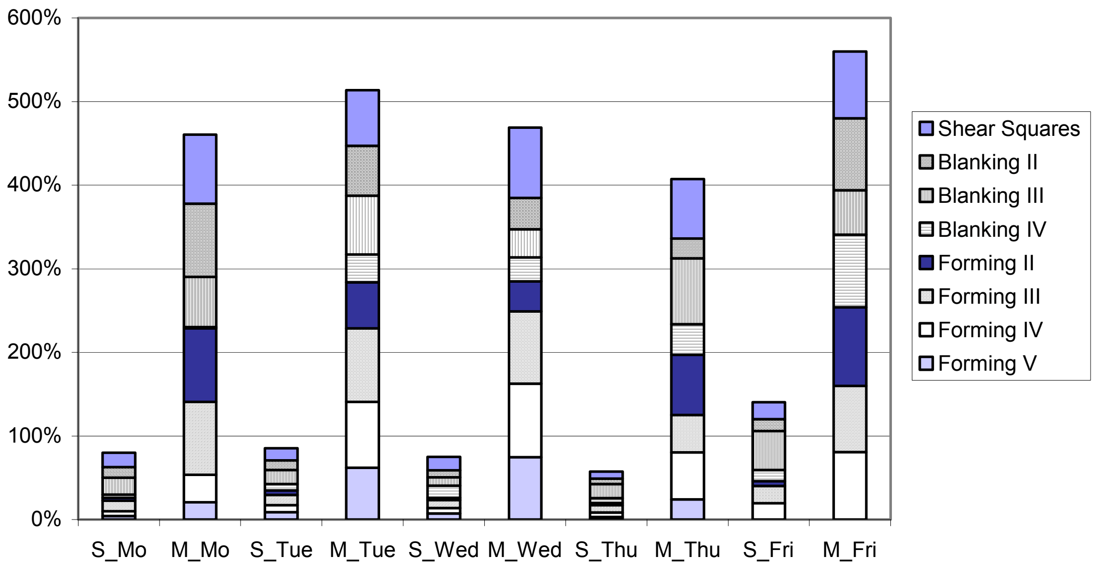

Figure 6.4 The Planned Average % Time of resources being in *Make* and *Set-up* states

The interpretation of the SC results presented in Figure 6.2 and Figure 6.3 is validated by the values of the classical performance measures, i.e. the planned average % time of resources being in state *Set-up* and *Make* presented in Figure 6.4, Figure 6.5 and Figure 6.6, respectively.

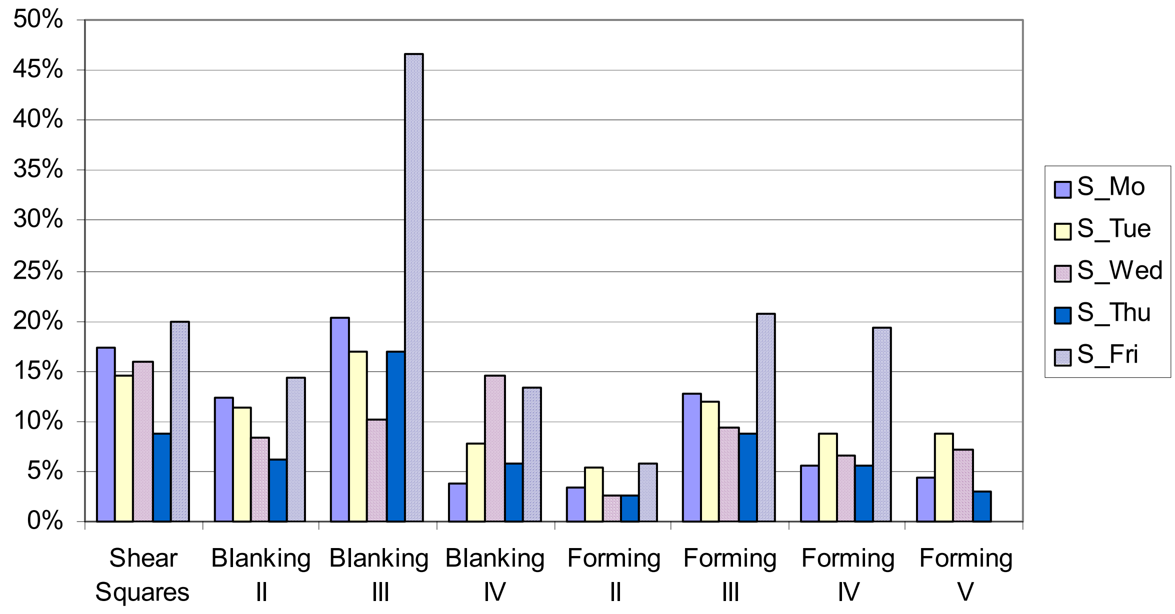

Figure 6.5 The Planned Average % Time of resources being in state *Set-up*

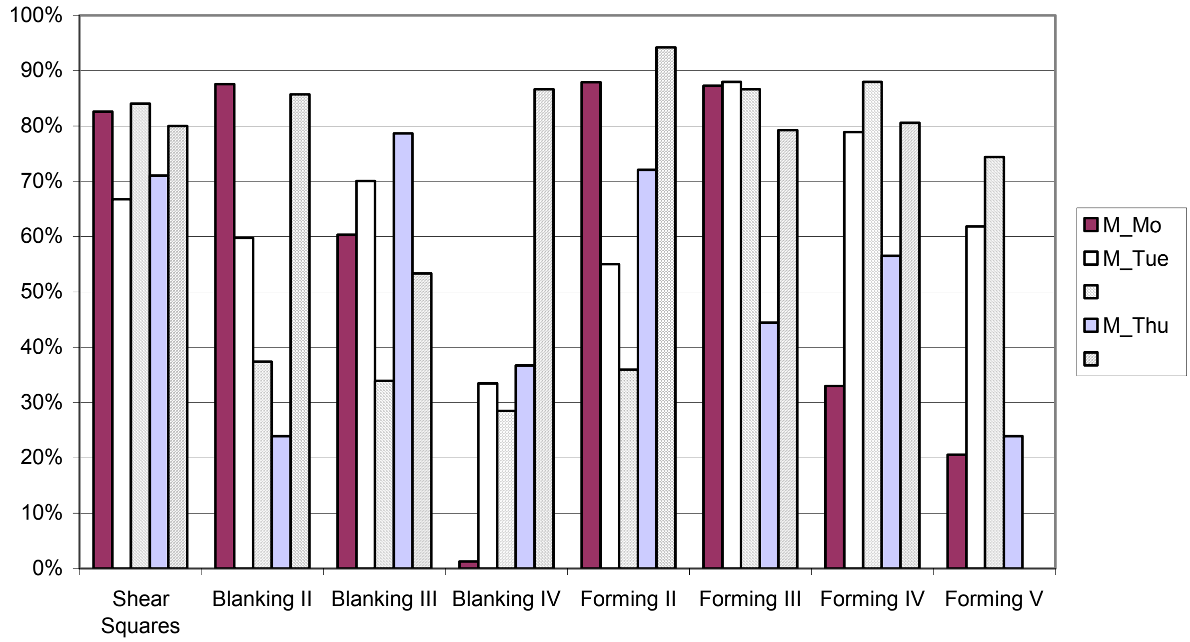

Figure 6.6 The Planned Average % Time of resources being in state *Make*

6.5.2 Operational complexity: How things have actually happened and why

For the OC calculation, the state definition at each resource include:

- *In Control*: *Make*, *Set-up* or *Idle*
- *Out of Control*: *Waiting Set-up* (WS), *Fitter* or *Waiting Fitter* (F), *No Operator* (NO)

The problem that this state definition can identify is the extent of deviation from the expected behaviour, in terms of resources not being in the planned state, and the reasons for these deviations. The total OC obtained are presented in Table 6.5. The highest OC is obtained for Monday, with the second highest for Thursday. Overall, the OC for the five days are very close together. Furthermore, the results in Figure 6.8 indicate a similar pattern of variation for the *In Control* versus *Out of Control* states throughout the week.

Table 6.5 The day-specific OC

Day	Number of parts	OC
Monday	24	11.07
Tuesday	25	9.671
Wednesday	19	9.676
Thursday	18	10.61
Friday	12	9.676

The resource type-specific OC are presented in Figure 6.7. These results can be linked with the reason-based analysis in Figure 6.9 and the analysis of the actual average time in states *Set-up* and *Make* (Figure 6.10), in order to identify critical problems such as poor scheduling policies, high absenteeism, or insufficiently skilled people. These results indicate two major critical reasons for deviating from the expected behaviour: *No Operator* (NO), and *Waiting Set-up* (WS). These results confirm several of the problems identified in the familiarisation phase, such as High Absenteeism (Section 6.4).

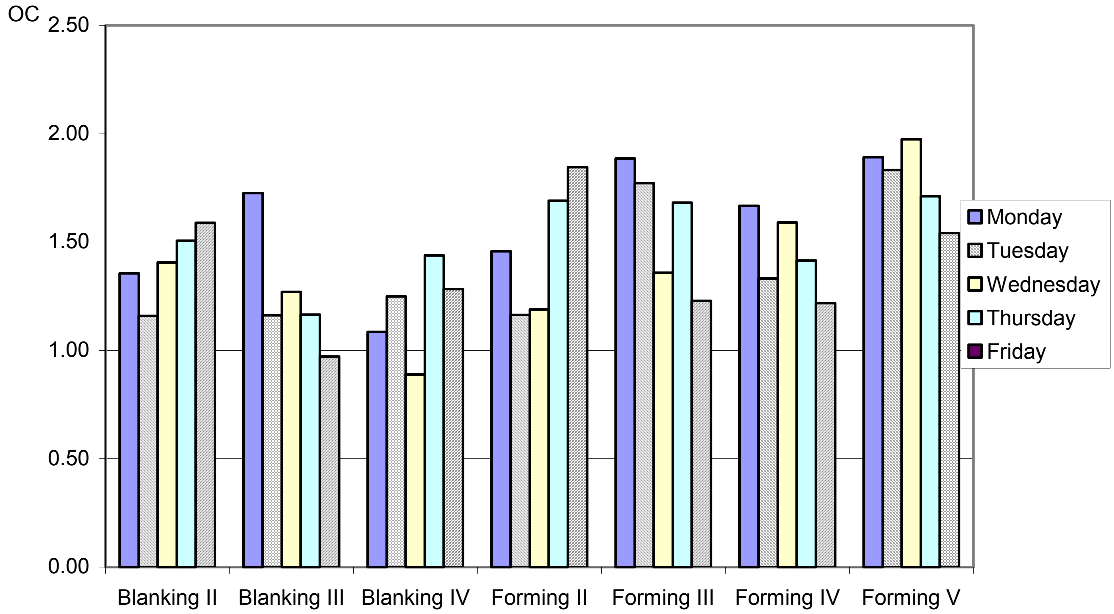

Figure 6.7 Resource type-specific OC

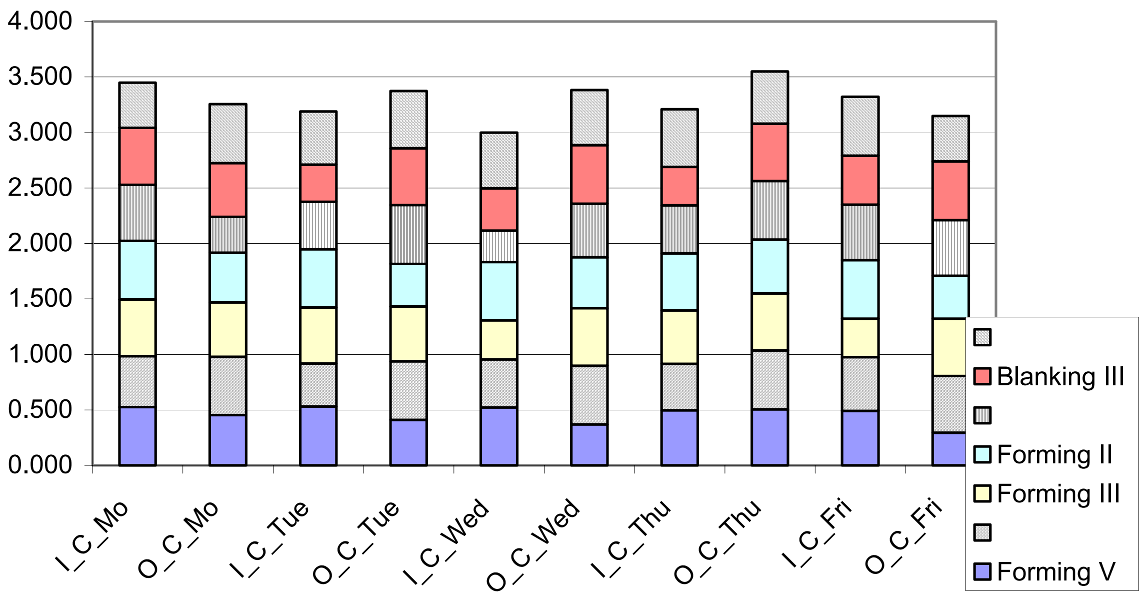

Figure 6.8 The *In Control* (I_C) versus *Out of Control* (O_C) OC (Equation 4.3)

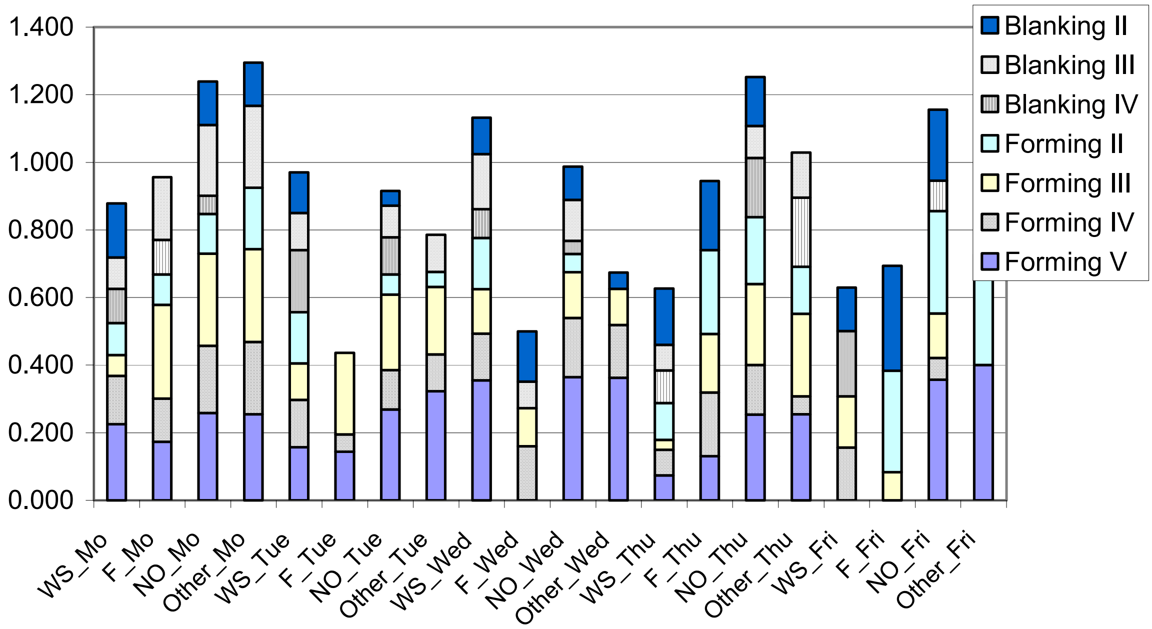

Figure 6.9 The state-based constituents of the *Out of Control* OC

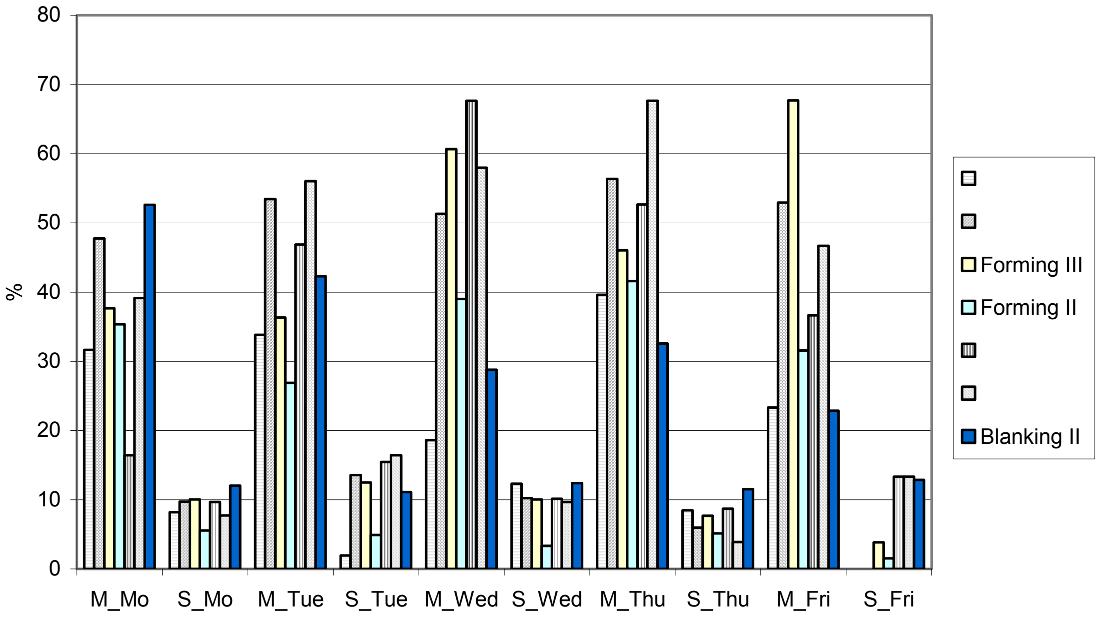

Figure 6.10 The Actual Average % Time in states *Set-up* and *Make*

6.5.3 How things might happen: The home line based SDMC

A brief example of how things might be improved consists of an investigation of the effect of allocating products to home lines (HL) (i.e. an operation for a product can only be performed on a single resource) on SDMC. The resources on which the products can be produced have been allocated randomly, starting from the operational product set defined in Section 6.5.1.1. As shown in Table 6.6, a significant reduction in the SDMC for the new configuration was obtained.

Table 6.6 Day-specific home line (HL) SDMC

Day	Number of jobs	Number of SDMC-contributing elements for the HL configuration	Number of SDMC-contributing elements of HL/actual Number	SDMC (HL)	SDMC/ SDMC (HL)
Monday	24	5375	90.757	11.923	1.552
Tuesday	25	6920	109.542	12.271	1.557
Wednesday	19	4121	92.396	11.3	1.582
Thursday	18	2745	104.169	10.82	1.626
Friday	12	1396	118.578	10.006	1.689

6.6 Application of the manufacturing complexity framework: Discussions and assessment of the methods

For the one-week case-study presented in this chapter, the SDMC, SC and OC values for the analysed facility have comparable values. The problems detected and assessed by applying the complexity measurement framework include poor scheduling practices (uneven load throughout the week, reflected by the SC indices), high absenteeism and critical competencies (through the OC values corresponding to the *No Operator* and *Waiting Set-up* states,

Figure 6.9).

Table 6.7 Additional types of information-theoretic analyses

No	Type of Analysis	Issue investigated and assessed	Benefit
1.	Calculate SDMC and SC for various home-line or Group Technology strategies	The impact of re-design strategies on the complexity of controlling the system	Support decision-making in the system design phase
2.	Calculate SC and OC for a more detailed state definition, such as product-specific state definitions (Set-up Product A, Make Product A)	The individual contribution of each product to the amount of information required to monitor and control the system	Identify problem parts Identify critical lot sizes
3.	Calculate SDMC, SC and OC for historical data	Long-term structural and operational parameters	Identify recurrent long-term problems, such as unfeasible schedules, faulty resources, quality problems
4.	Calculate the cost of material, labour, resource versus added-value and complexity	Quantify the trade-off between the cost of running and controlling the production and the added-value	Identify critical parts (low value-adding products with high production and control costs), and consider outsourcing or other methods to increase efficiency
5.	Include labour skills, and resource and product-specific labour requirements in the modelling	Quantify the impact of more complex state definitions and of tasks consistently requiring several resources on SDMC, SC and OC	Identify critical competencies and direction for action

The resource type-specific state definition significantly reduced the OC values for the system. This definition covered only the issue whether the resources are producing or not. The issues that remain to be investigated include whether the "right" quantity of the "right" product at the "right" time is produced. Variations in any of these dimensions will affect the OC levels. Furthermore, the SDMC method could be used to calculate a more realistic value of SDMC, as re-scheduling is frequently performed in the analysed facility.

Additional types of information-theoretic investigations that may be performed and their potential benefits are presented in Table 6.7.

6.7 Summary

This chapter has presented methodological issues related to the application of the manufacturing complexity framework presented in this thesis in practice. Several case studies in which individual measures of complexity have been calculated, the issues identified and the lessons learned have been briefly presented. The identification and assessment of critical issues in a case study through SDMC, SC and OC have been illustrated, and several links with classical performance measures have been suggested. The predictive capabilities of SDMC have been exemplified by investigating the impact of layout re-design on SDMC.

7 Conclusions and further work directions

The important thing is not to stop questioning.
Albert Einstein [Ein+]

One never notices what has been done; one can only see what remains to be done.
Marie Curie [Cur]

7.1 Summary of contributions and conclusions

This thesis has made advances in the theoretical definition, measurement and control of manufacturing complexity. The information-theoretic approach taken in this thesis integrates the various structural and operational dimensions of discrete-event systems in a set of unified and meaningful measures, intrinsically applicable to manufacturing. The ultimate contribution of this work consists of a powerful set of information-theoretic methods for identifying and assessing cause-effect relationships, and therefore for achieving an objective and systemic understanding of the issues present in manufacturing. The quantitative approach allows comparisons to be made between the complexities of various facilities, or between different moments in time within the same facility. The approach also provides an objective basis for prediction, control and priority definition.

By comparison to classical performance measures which capture static parameters of the system, the information-theoretic measures capture the dynamics of the system. Furthermore, this thesis has made advances towards a generic, meaningful, valid and transferable methodology for measuring complexity.

The main contributions of this thesis are based on the understanding that structure, material, information and money flows are intrinsically linked in manufacturing, and should be analysed and managed as such. The monetary aspect is captured by recording and analysing the reasons for customer changes, and via the policies used for scheduling or re-scheduling.

Specific contributions of the thesis include:

1. *Identification of the need for a realistic and comprehensive definition of manufacturing complexity* (Chapters 1 and 2).
2. *Assessment of previous information-theoretic approaches to the measurement of various aspects of manufacturing complexity* (Chapter 2).
3. *Identification and assessment of the sources of complexity in a kanban-based system characterized by process variability through simulation* (Chapter 3 and Section 5.3).
4. *A realistic and comprehensive definition of manufacturing complexity*, soundly founded on the understanding gained through literature review, analytical modelling and simulation, and case-studies (Section 4.1).
5. *Information-based conceptual definitions of structural and operational complexity* (Sections 4.3.1 and 4.4.1).
6. *Advancement in the methodology for the measurement of structural and operational complexity* (Sections 4.3.2 and 4.4.2).
7. *Identification and justification of the need for a third major class of complexity, scheduling-relating decision-making complexity* (Sections 4.1 and 4.2).
8. *An information-theoretic definition of scheduling-related decision-making complexity* (Section 4.5).
9. *The innovative concept of value of complexity in manufacturing*, *closely related to flexibility* (Sections 4.1, 4.2 and Section 4.5).
10. *A software tool for assessing scheduling-related decision-making complexity*. Although the code has not been included in the thesis, the results presented in Chapter 5 and Section 6.5 have been obtained using this tool. Therefore, the tool contributed to the validation of the methodology.
11. *Dissemination of results to academia and industry*. The results of the work on manufacturing complexity presented in this thesis have been published as a first author or co-author in

several books chapters, and as journal, magazines, and refereed international conference papers. On the practical side, the methods presented in this thesis, or extensions of these methods, have been validated in a large number of case studies, in various industries. The applicability, validity and usefulness of the framework have been illustrated in Chapters 5 and 6.

7.2 Further work directions

Several appealing research directions have emerged from the work reported in this thesis. They are presented next.

7.2.1 The cost and value of complexity

The development of a theoretical and practical methodology for quantifying the cost and value of complexity in manufacturing would be a natural extension to the work presented in this thesis. This would offer:

- A cost and value-based understanding of the cause-effect relationships in manufacturing, such as:
    - Who should pay, and how much, for additional sources of complexity – the customer or the company itself?
    - What are the non-value-adding components of complexity, and what would be the economic impact of removing or better controlling them?
    - What are the qualitative and quantitative trade-offs between the cost and the value of complexity?
- Support for cost- and value-based decision-making and prioritising.
- The cost/complexity and value/complexity measures would represent a platform for comparing different entities (such as organisations or supply chains). This is particularly

valuable as we consider that it is not enough to compare the absolute values of the cost/value and complexity in order to decide which entity is more value adding.

7.2.2 Mathematical analysis of the individual properties of SC, OC and SDMC, and of their joint properties

More analytical work is required to reveal individual and joint properties of SDMC, SC and OC. Several promising research directions include the definition of time-comparability on an analytical rather than experimental basis, and the investigation of the link between systems with assembly/ disassembly systems on SDMC.

7.2.3 Applied research directions

The application and validation of the methodology in practice has proved invaluable for the work reported in this thesis. Further work is required in order to investigate the effect of rescheduling on SDMC, and on the levels of system performance, predictability and control, as well as to further validate and extend the methodology.

Enhanced capabilities could be implemented in the SDMC software tool, and potential new exploitation directions could be investigated.

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