THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

On System Dynamics as an Approach for Manufacturing Systems Development

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Göteborg, Sweden 2009

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ABSTRACT

Improvement work in manufacturing industry usually focuses on the utilisation of equipment. System dynamics simulation is a potential tool for increasing the utilisation of systems. By using group model building and simulation it facilitates a common view and better informed decisions for change. However, a gap between theory and practice of how to *implement* these projects is identified, consequently the major question for this thesis.

The approach for solving this problem used industrial case studies with action research character; including modelling and interviews affecting the actors in the studied systems. Together with literature studies these efforts contribute with identifying how system dynamics projects can be performed for manufacturing systems development.

It is shown that the support for how to *implement* system dynamics projects is unsatisfying and general. During the research progress a *framework* of guidelines has crystallised in order to bridge the presented gap of this thesis. Finally, the results are considered to make it easier to support manufacturing systems development using system dynamics.

Keywords: system dynamics, manufacturing systems development, operational management, decision support for change, group model building

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LIST OF PUBLICATIONS

APPENDED PAPERS

Paper A Linnéusson, G., Jägstam, M. and Näsström, C. (2008). *Cutting Tool Management: A Dynamic Assessment of Opportunities for Improvement.,* Proc of the 18th International Conference on Flexible Automation and Intelligent Manufacturing, Skövde, pp 1084-1091.

Paper B Linnéusson, G. and Jägstam, M. (2008). *On Applying a Systems Approach to Manage Operative Improvements in Manufacturing SMEs.*, Proc of the 14th International Congress of Cybernetics and Systems of WOSC, Wrocław, pp 612-621.

Paper C Linnéusson, G. and Jägstam, M. (to be published). *Machine Strategy Evaluation Using Group Model Building in System Dynamics.*

ADDITIONAL PAPERS

Linnéusson, G. and Jägstam, M. (2007). *Manufacturing Organization Development Efficiently: Using System Dynamics.,* Proc of the 8th System Dynamics PhD Colloquium, Boston, pp 45-55.

Linnéusson, G. and Jägstam, M. (2007). *On a Support that Simulate Change Management in Manufacturing.,* Proc of the 1st Swedish Production Symposium, Gothenburg.

Karlsson, D. and Linnéusson, G. (2008). *Systemic Change Management: An Opportunity for Manufacturing Organizations.,* Proc of the 18th International Conference on Flexible Automation and Intelligent Manufacturing, Skövde, pp 654-659.

Linnéusson, G. (2008). *System Dynamics as a Change Management Tool in Manufacturing SMEs.*, Proc of the 2nd Swedish Production Symposium, Stockholm.

Linnéusson, G., Jägstam, M. and Kinnander, A. (2009). *Bridging a Methodological Gap in Using System Dynamics in Manufacturing.,* Proc of the 3rd Swedish Production Symposium, Gothenburg.

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ACKNOWLEDGEMENTS

This thesis would not have been written if not Andreas Mehner would have phoned me home on my parental leave, with Elsa 1 year old, in autumn 2004 and asked me to. It was the best of timing. Two years later and when my second daughter Irma was 1 year old these studies started. The opportunity to perform this pioneering production research has been gratefully performed and a challenging intellectual exercise. When writing these words my wife Linda is home on parental leave with our half year old son Birger and our daughters. They are my family and have been there through the times past and if we may live, times to come, I love you.

On this page I would also like to acknowledge people that have supported or had importance for me during these years: Andreas Mehner, Mats Jägstam, Kjell Carlsson, Jan Oscarsson, Anders Kinnander, Christer Johansson, and other fellow researchers at research school CAPE and at University of Skövde. Colleagues at Arkivator: Anette Melin, Christer Näsström, Maria Andersson, Östen Friberg, those of you who have taken part in my research case studies, and others. External colleagues: Daniel Karlsson, friend and co-writer in one of the additional papers. Neramseen Khamou, friend in AnyLogic ☺. Emil Andréasson, friend in X and English expert.

Falköping, autumn 2009
Gary Linnéusson

1 INTRODUCTION

"The only constant is change" (Heraclitus, wikiquote 2008)

Change is an inevitable development that manufacturers have to comply with. The demands on manufacturers are increasing on several levels: higher profit, more complex products, shorter lead-times and increased competition on a global level, to name a few. To manage successful change is a complex undertaking. One significant aspect is the complexity of taking in the whole picture from decisions for change to its consequences.

Moreover, for operational management in manufacturing, change includes both social and technical aspects. One main social aspect is that people carry with them individual mental models of their manufacturing systems. This bears two important consequences. Firstly, the consequences of how people act depending on the information they have. And secondly, the consequence from individual perceptions of problem phenomena when it comes to how change for improvement is carried out in these systems. The social side of manufacturing systems is a complicating factor on technical systems already complex, easily neglected in production engineering.

Reasons to conduct the research presented in this thesis have been:

1. Manufacturing industries need to increase their ability to produce more efficiently and lean in order to be profitable. To accomplish this, changes must lead to improvements and be operative.

2. System dynamics projects are used for assuring operative changes. It is a method for identifying and improving behaviours of social and technical systems.

Item 1 is a general fundamental condition for motivating any production research. Item 2 suggests system dynamics (Forrester 1961; Sterman 2000)

as a methodology that out of several possible ones could attain item 1. The opportunities for system dynamics in manufacturing is stated previously (Baines and Harrison 1999). System dynamics approach both hard parameters, traditionally made in manufacturing systems improvement, and soft parameters in social systems; such as delayed information, experience development, habitual behaviour, and etcetera. Understanding of underlying system behaviour is generated using system dynamics modelling, a system language for explaining the problem phenomena. During model building people's different mental models is acknowledged and put into a common model, which may facilitate for better informed decisions for change.

Further, applying system dynamics as a management tool in manufacturing has a potential to overcome the "missing link in corporate strategy" (Skinner 1969). Skinner's solution for that is that top management actively would manage manufacturing through the making of policies, which makes it applicable to use system dynamics for this effort. Also, system dynamics use existing knowledge in order to identify improvements. This procedure may prevent generating yet another inefficient system, otherwise the risk in improvement programs to create new better systems (Nelson 2000). Thus system dynamics has a perspective for manufacturing systems development that is interesting to explore, the main argument and core of this thesis.

1.1 PLACING THE PROBLEM IN ITS CONTEXT

The research problem is represented by a gap between system dynamics theory and how to practically implement such project in manufacturing industry. A symptom of the gap regards usage of system dynamics at Swedish manufacturers. Few such applications have been found: business strategy (Montán et al 2000); business planning (Sixtensson et al 2000); configuring of manufacturing systems (Tesfamariam 2005); and using cost models (Storck and Lindberg 2007). On an international level a study by Baines and Harrison (1999) identified 8 out of 80 papers (from 1990-1995) that applied system dynamics in manufacturing. Further, searching for courses on offer on the subject at the ten largest universities in Sweden (Andersson 2008) showed a poor result. Two available courses that approach system dynamics in their syllabus were found.[1] One of them was applied for in spring 2008; however there were too few interested and it was

cancelled from schedule. Searching for Swedish consultancies that offer services based on system dynamics also showed a poor result; two could be found.[2] On contact they replied: yes, we offer system dynamics simulation, but no services had been sold to any customers yet. Altogether these findings support the statement of a low use at Swedish manufacturers and motivate this research.

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1. Available courses at the ten largest Swedish Universities that approach system dynamics, the last search was conducted in June 2009:
- Design support systems in industrial management, IBS092, Department of Teknikens ekonomi och organisation, Chalmers University of Technology.
- Advanced Project Course, AH2111Logistics, Department of Transport and Logistics, Royal Institute of Technology.

2. Consultancies in Sweden that provide system dynamics services in Feb-Mars 2008:
- Acierto, VD Carina Ullemar Lönnbom, Tekn. dr., Kista, with Swedish technical partner Carubel AB, Sollentuna.
- Trilogik, Part owner Göran Berggren, Stockholm.
- McKinsey in Sweden was contacted and they did not offer any system dynamics services.

1.2 THESIS STRUCTURE

In order to guide the reader this chapter summarizes the structure of the thesis.

Introduction

Aspects for this thesis to address, containing: background, reasons to motivate the research and a brief description of the problem context.

Research Approach

The objectives with the research are presented together with: the thesis' boundaries, research characteristics in terms of a systems thinking view and the aspects of applied and theoretical research, and validation aspects for this qualitative explorative research.

System Dynamics

The frame of reference chapter, containing: the fundamentals of system dynamics, modelling aspects relevant for this thesis and reviews of areas in larger contact with the objectives; group model building and modelling process descriptions.

Findings

Include reviews of the appended case studies. Presents a gap analysis, reviewing: the identified lack of use, other approaches to increase use and important aspects to bridge in *operations management* applications of the system dynamics methodology. Presents and motivates the developed *framework* as a mean to bridge the identified gap.

Summary and Conclusion

The thesis is closed with a discussion on the achieved results and the final conclusions. The fulfilment of objectives and validation issues are discussed, the conclusion summarizes the thesis and the procedure for further research is noted.

2 RESEARCH APPROACH

2.1 OBJECTIVES

The research objective is to *increase an organisation's ability to find key leverage points in an industry problem situation by using system dynamics.* In order to attain this, the thesis focuses on *implementing* system dynamics projects for manufacturing systems development. One research question is defined in this area to be answered by this licentiate thesis:

> *Q1: What are the key enablers for bridging the identified gap between academic theory and industrial practice, of how to implement a system dynamics project for manufacturing systems development?*

The result of searching for the answer to Q1 is represented by a foundation to build further research on; a *framework* is developed for support using system dynamics projects for manufacturing systems development.

2.2 DELIMITATIONS

The delimitations focus on using system dynamics for manufacturing systems development. This excludes using other methodologies for such development. And it is not of current interest to look into the combination of system dynamics with any other methodology. Thus, the research boundaries of this thesis can be organised as:

- *Industrial branch*: Medium and large sized manufacturing companies with production characterised by reoccurring structural problems. Large enough companies are slow to change, due to size of organisations, and have the financial strength to invest in eliminating such problems.

- *Business improvements area:* Manufacturing systems involving *operational management* such as leaders and experts from functions in direct contact with the undertaken problem. Purpose is to include persons from the organisation that are keen on solving the problem,

which facilitates a successful project. Moreover manufacturing systems are here defined, not on a level of equipment utilisation, but on a system level placing focus on how the information that govern a system is structured and dynamically behave. This level includes how humans interpret and operate manufacturing systems. For the remainder of this thesis the use of the word manufacturing systems aims on this system level. The Cases described in this thesis provide examples of problems on a system level.

- *Project focus:* On redesigning and improvement phases of manufacturing systems. Mapping a system's problem behaviour in order to identify change for improvement.

- *Simulation domain:* System dynamics simulation using group model building. It is performed within the previously described *Project focus*, *Business improvements area*, and *Industrial branch* above.

2.3 RESEARCH CHARACTERISTICS

The content of this thesis is characterised by theoretical and applied research as well as the systems thinking perspective defined below. The manufacturing context of the research makes it natural to search for practical use from results.

2.3.1 A Systems Thinking View

Systems thinking can be defined as:

> *"The central concept 'system' embodies the idea of a set of elements connected together which form a whole, this showing properties which are properties of the whole rather than properties of its component parts. … The phrase 'systems thinking' implies thinking about the world outside ourselves, and doing so by means of the concept 'system'." (Checkland 1988, p 3)*

Systems thinking acknowledges a holistic perspective on the studied question. *Implementing* a system dynamics project for manufacturing systems development requires taking a holistic perspective on the studied problem. This also influences the qualitative interpretive character of this explorative research. These aspects limit the possibilities to perform

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multiple tests, otherwise common when studying a defined subject which generates a result built on quantitative data. This implies that this thesis aims at answering a question through interpreting a few samples, instead of supporting a hypothesis through a satisfying amount of samples.

2.3.2 Theoretical and Applied Research

In order to conduct applied research there has to be theoretical research and vice versa. An overview of the character of this relation for this research is shown by figure 1.
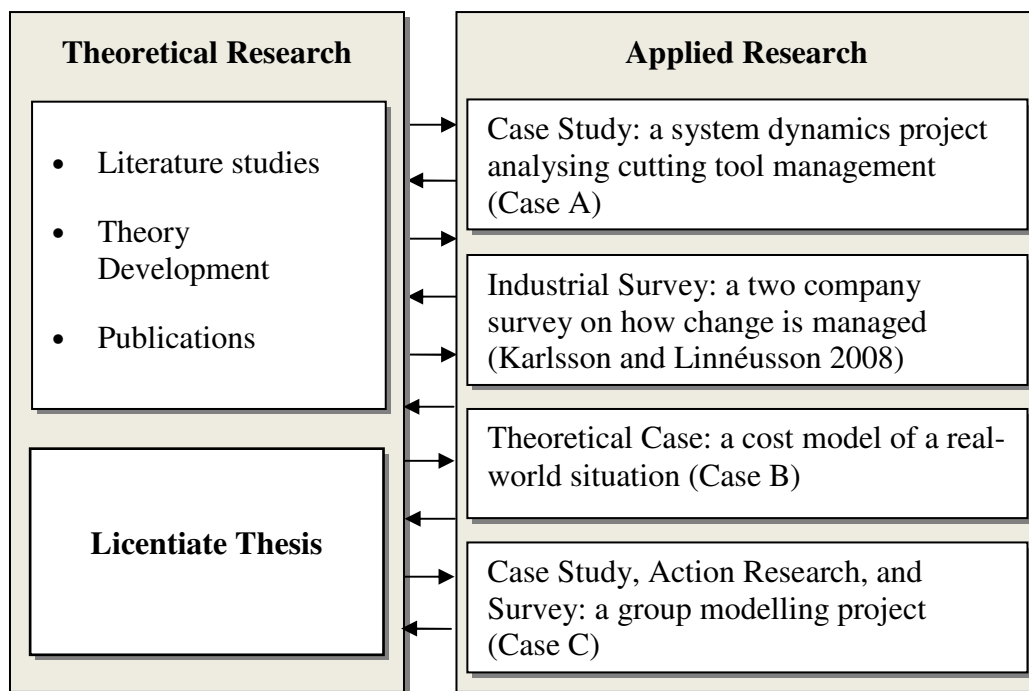
Figure 1   Overview of theoretical and applied research characteristics

The research has had a theoretical focus of: literature studies, how to apply the findings and formalise them into theory, and in publications. However, the theoretical side of research has been interwoven with applied studies in order to provide with results that are not possible to achieve through readings alone. The aspects of this research, seen in figure 1, are:

- *Literature studies* have had the main purpose to orientate within the field of system dynamics in order to explore its methodological underpinnings and practical knowledge of simulation. The purpose was also to identify the field's research problems in relation to the practical

implementation in a manufacturing context. The case studies empirically support that purpose. Literature studies have occasionally also regarded: cutting tool management (Case A), systems thinking (Karlsson and Linnéusson 2008), and change management (Case B; Linnéusson 2008). In these occasions the purpose has been to orientate within a subject and not to reach expert knowledge.

- *Theory Development* is a natural product of the literature studies and benefits from testing the system dynamics methodology. Figure 2 in the next chapter illustrates the incremental behaviour of theory development towards the result of this thesis.

- *Publications* during research progress are the result of achieved theory development. It has reinforced the incremental behaviour of theory development through feedback from peers into the research project.

- *Applied research* has mainly aimed at performing tests of *implementing* the methodology of system dynamics on real problems, representing empirical findings. Implementation of simulation results in the real system have been excluded and regarded outside the delimitation of the thesis.

The applied qualitative research has been interpretive which can be defined:

> *"Interpretive approaches with an interactive research strategy perhaps only codify the best of common sense, insights, wisdom, sound judgement, intuition and experience. But the differentiating factors between personal everyday interpretation and opinion is the scholarly demands of being systematic, connected to theory, and be as transparent as possible by publishing the research and making it accessible for the academic community and business." (Gummesson 2003, p 491)*

The system dynamics methodology has an interpretive character in the process of data collection for modelling. However, the case studies differ in this approach. Case study A and B did not during their progress affect the modelled system. However, Case C was made in a group setting including the researcher. The researcher was included in the change process during the study. This characteristic is typical for action research, defined as:

> *The concept of action research arises in the behavioural sciences and is obviously applicable to an examination of human activity systems carried*

out through the process of attempting to solve problems. Its core is the idea that the researcher does not remain an observer outside the subject of investigation but becomes a participant in the relevant human group. The researcher becomes a participant in the action, and the process of change itself becomes the subject of research." (Checkland 1988, p 152)

2.4 RESEARCH PROCEDURE

The progress of the research has evolved in an iterative character, shown by figure 2.
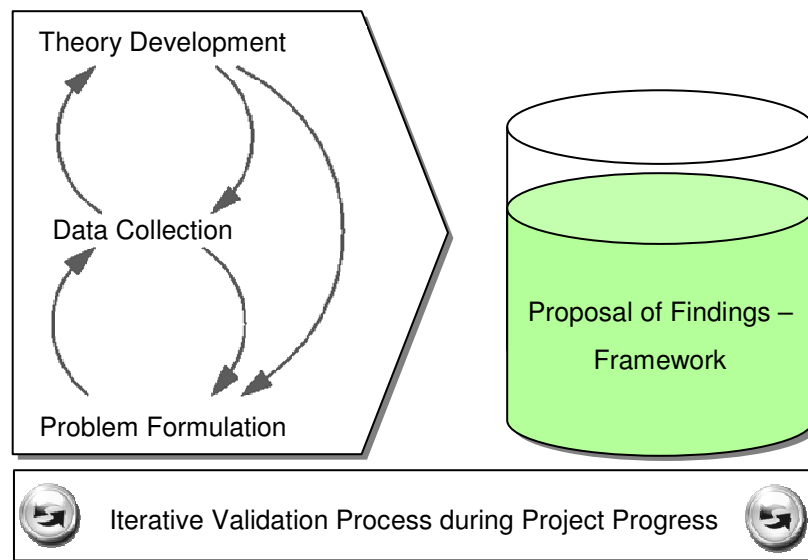
Figure 2   The iterative process steps in the research procedure

The figure includes the following elements:

- *Problem Formulation:* The basis of the research. It is a progressive moving target comprised of: objectives, research question, and delimitations for the project. The *problem formulation* implies on which *data to collect*.

- *Data Collection:* Literature studies carried out mainly within the field of system dynamics and in empirical action research case studies. The findings from *data collection* sharpen the *problem formulation* or reject it, simultaneously the findings impact on *theory development* in a similar behaviour.

- *Theory Development:* The findings are processed in order to formulate an answer to the research question. Generally *theory development* follows the principle of abduction which is a combination of induction (starts in empirics) and deduction (starts in theory), and is considered the most common procedure in case study based research (Alvesson and Sköldberg 1994). However it can be difficult to establish what comes first – the studying of empirics or theory – it depends on situation and pre-knowledge. Therefore figure 2 illustrates the procedure as an iterative procedure which does not have an obvious starting point, or indeed a finishing line. Thus, *theory development* is strongly dependent on the *collected data* and affects the *collection of data*. This occurs for example when an interesting subject is uncovered and new data is needed. Further, the results may have consequence for *the problem formulation*.

- *Proposal of Findings – Framework:* This element represents the accumulated research outcome at any given moment and for this thesis it includes presenting a framework.

- *Iterative validation process:* see validation section below.

2.4.1 Validation

Validation is fundamental for the research procedure, which is pictured in figure 2. The validation box is the fundament for the other boxes and has two characteristics:

- During research procedure validation has verified that the aim for this thesis has been approached, an iterative process of constantly judging upon achievements. This is due to the explorative character of the research question.

- Validation of research results: case studies have been used to gather empirical data in order to support an answer to the research question and on the theoretical level conclusions are drawn from observing literature.

The validation of this thesis excludes testing the developed methodology. As previously mentioned the results are qualitative and can be difficult to validate. However, the qualitative approach of this research is not novel in any sense. Instead of using the traditional view of performing multiple tests

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to assure validation, the qualitative character uses a view where results from real world phenomena have to confirm to analytic generalisations from few samples (Wiktorsson 2000). In order to cooperate with the qualitative character a set of factors have been suggested by Olesen (1992) to validate research results. His framework for validation has been used by others also having a qualitative research character (Jägstam 2004; Klingstam 2001; Nelson 2000). Therefore it is used in this thesis. These factors are used in the discussion in order to state the level of validation for this thesis. Olesen's factors, quoted from (Klingstam 2001, p 14), are:

- *Internal logic*: The results are based on known and accepted theories, and there is a logical sequence connecting the research problems, hypothesis, and the results.

- *Truth*: The theoretical and practical results can be used to explain "real" phenomena.

- *Acceptance*: Other researchers accept theories used in the research, and professionals are willing to use tools based on the theories.

- *Applicability*: Application of the results increases the probability of successful problem solving. It does not necessarily lead to success every time, but over a period of time it will give better results than if not applied.

- *Novelty value*: New solutions are presented, or new ways of looking at a particular problem introduced.

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3 SYSTEM DYNAMICS

"The essence of system dynamics is that it is a body of theory dealing with information feedback systems." (Vennix 1996, p43)

System dynamics has an engineering approach to analyse social systems. The system view shares the basis with servomechanisms where the regulation of the system is continuously monitored by feedback. It focuses on the structure of problem situations, the information flows affecting a system's behaviour, practically copying the decision making processes.

System dynamics started to develop in the 1950s at MIT (Massachusetts Institute of Technology) by Prof. Jay W. Forrester. At that time it was termed Industrial Dynamics (Forrester 1961). It was developed as a response to the inadequacy of conventional management science (Forrester 1960). Then current areas of research in operations research (management science) and mathematical economics were considered tackling too simple situations for real implementations.

Through the years the system dynamics method has evolved from industrial dynamics to a range of areas: fishing industry (Maani and Cavana 2007); oil industry, studying epidemics, innovation diffusion, and the growth of new products (Sterman 2000); problems of defeating drugs (Morecroft 2007); managerial interventions (Akkermans 1995; Akkermans and Bertrand1997; Maani and Li 2004); shipping industry (Vennix 1996); and strategy dynamics (Warren 2002).

3.1 PROBLEMS IN THE FIELD OF SYSTEM DYNAMICS

Eight problem areas for the future survival of the system dynamics field are identified by the leading professional George Richardson (1996). In different procedures these areas have had continuing effect on the present situation of system dynamics usage on an international level and in Sweden. These problems are:

1. Understanding model behaviour
2. Qualitative mapping and formal mapping
3. Confidence and validation
4. Accumulating wise practice
5. Advancing practice
6. Accumulating results
7. Making models accessible
8. Widening the base

The three first areas are approached in separate chapters: Understanding Model Behaviour; Qualitative or Quantitative Modelling; and Validation of Models. The remaining problem areas (4-8) are here reviewed and approached in brief:

4. Accumulating wise practice: The field lacks "the wisest statements about modeling practice" (Richardson 1996, p 3); no improvements have been identified in literature. The underdevelopment of this problem supports one of the arguments in this thesis; Unavailability: the difficulty in attaining information of wise modelling practice (Richardson 1996).

5. Advancing practice: Reaching the level above introduction is done either at universities, where such practice exists, or through time consuming reinvention on the field. This problem area is not approached on a general level, however on a specific level this thesis advances practice for manufacturing systems development.

6. Accumulating results: Should be done in order to prevent the tendency of reinventing other's work and promotes extraction of existing work by other practitioners. This problem area has developed through research in generic patterns of systems, for example (Winch and Arthur 2002; Wolstenholme 2003 and 2004; Rockart 2004: Chomiakow 2007). Providing defined

generic structures will not be part of this thesis, it may in fact cause difficulties for commitment to model ownership; since, "companies like to feel that they are unique and need to discover their own internal generics from their own specifics" (Wolstenholme 1997, p 3).

7. Making models accessible: "How can formal models be designed, formulated, and presented so that they are accessible to the widest possible audience?" Understanding is key for accessibility, therefore improvements have regarded: simplifications of model structure, sector mapping and space-compression objects (Richmond 1994), and including variable behaviour graphs when presenting a model (Warren 2005). One IT-based improvement is model attachments to conference papers at the homepage of System Dynamics Society. This thesis does not solve this problem situation. However using group model building has the consequence of smaller models (Barlas 1996), and a target group is defined - "manufacturing people" which may facilitate accessibility for that group of users.

8. Widening the base: "The future of the field of system dynamics rests on our abilities to widen its base, the population understanding the significance of feedback and circular causality in living systems." This global problem is not approached by this thesis. However if this problem area had developed in the past this thesis' question might already been answered.

3.2 A SYSTEMS THINKING METHOD

System dynamics is an approach to systems that belongs to a discipline termed systems thinking, which has evolved during the 20th century (Lawson 2006). Generally systems thinking methods can be categorised as systemic approaches to achieve understanding of a studied system (Flood 1999). The basic theory of such method describes how systems are comprised and fundamentally functioning or how they can be studied. Hence it provides a tool for understanding systems, for instance a manufacturing system, and how to improve them. Systems thinking is a 'terminology' that "has no clear definition or usage" (Forrester 1994, p 10) and it shows through the range of methodologies within this discipline, such as: "cybernetics and chaos theory; gestalt therapy; the work of Gregory Bateson, Russel Ackoff, Eric Trist, Ludwig von Bertallanffy, and the Santa Fe institute" (Senge et al 1994), and Soft Systems Methodology (Checkland

1988). And some systems thinking terminologies provide with theories regarding system's ontology, for instance:

- *The viable systems model* (Beer 1994), a diagnostic tool that "map the extant organization onto the model, and then ask whether all parts are functioning in accordance with the criteria of viability" (Beer 1994, p 155).

- *The Soft Systems Methodology* (Checkland 1988), an analysis tool, or "learning system" (Checkland 1988, p 241), based on systems ideas in order to understand the studied system.

- *System dynamics* (Forrester 1961), uses the fundamental building blocks of systems, feedback structures of levels and rates, both to explain the "universal structure of real social and physical systems" (Forrester 1994, p 13) and for guiding the construct of a model of a system for analysis.

Thus, applying system dynamics for manufacturing systems development provides a tool for understanding problem phenomena and a tool for how to perform change in order to improve the studied system.

3.3 THEORIES

Four basic theories in system dynamics are important for this thesis. They can be divided into: hard, technical aspects of modelling and soft, social aspects of modelling, they are:

- Hard, technical aspects in modelling
    - Theory of Structure
    - Dynamic Complexity
- Soft, social aspects in modelling
    - Mental Models
    - Social Reality

3.3.1 Theory of Structure

The theory of structure reached a mature level already in 1968 (Forrester 1968) and is still used. Forrester (1968) stated that: in contrast to other

fields and bodies of literature, which also provides with philosophies of structure in systems, system dynamics provides with the sharpest definition and the most rigorous application of structure. The structure is represented by four significant hierarchies which are used when to model a system, from (Forrester 1968, p 4-1):

- The closed boundary
    - The feedback loop as the basic system component
        - Levels (the integrations, or accumulations, or states of a system)
        - Rates (the policy statements, or activity variables, or flows)
            - Goal
            - Observed conditions
            - Discrepancy between goal and observed conditions
            - Desired action

The closed boundary: a philosophical view (feedback thinking) that denotes that what crosses the boundary from outside has minor effect on the system behaviour. The line of boundary strictly depends on the modelled problem; the elements that generate the mode of the system must be included.

The feedback loop: the basic component of a decision making process. Decision making depend on the perception of the present system condition, and any decided change give rise for a new condition which influences our next decision.

Levels and Rates: the two classes of variables of a system dynamics model. "The level equations are integrations which accumulate the effects of the rates" (Forrester 1968). The levels describe the condition of a system, for instance the capability of a machine. The rates are the flows into or out from the levels, for instance investment in capability (flow into) or capability erosion (flow out from). The levels further carry the system's continuity from the past to the present and are the source of information to rate equations.

Goal, Observed conditions, Discrepancy between goal and observed conditions, and Desired action: the four components of the "policy substructure" in systems. The *goal* is the desired state of a system, for

instance an Inventory level (there may also be several conflicting goals in a system). The *observed condition* is the apparent state, the available information of the system at that time, and the information for decision (the true state of a system may be delayed or distorted by conditions in the system). The *discrepancy between goal and observed conditions* is the difference between the desired *goal* and the *observed conditions* and it results in a decision; the *desired action* to close the gap, for instance production need.

3.3.2 Dynamic Complexity

The two technical aspects belong to the "engineering part" of modelling and is the result of simulation (dynamics over time). Reality is dynamically complex, and the methodology of system dynamics is developed in order to capture these kinds of dynamics of systems. This implies thus that system dynamics is a language of dynamic systems. This property is an important aspect why system dynamics should be used for dealing with the dynamic complexity in manufacturing systems. However, applying the social dimension, described in the next two sections, includes how the dynamic complexity is generated and acknowledges that humans interpret systems differently. A list of reasons why dynamic complexity arise is included, paraphrased from Sterman (2000, p 22). Dynamic complexity arises because systems are:

- *Dynamic:* What appears to be unchanging is, over a longer time horizon, seen to vary. Change in systems occurs at many scales, and these different scales sometimes interact.

- *Tightly coupled:* The actors in a system interact strongly with one another and with the natural world. Everything is connected to everything else.

- *Governed by feedback:* Because of the tight couplings among actors, our actions feedback on themselves. Our decisions alter the state of the world, causing changes in nature and triggering others to act, thus giving rise to a new situation which then influences our next decisions.

- *Nonlinear:* Effect is rarely proportional to cause, and what happens locally in a system (near the current operating point) often does not apply in distant regions (other states of the system). Nonlinearity often

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arises from the basic physics of systems, and also arises as multiple factors interact in decision making.

- *History-dependent:* Taking one road often precludes taking others and determinates where you end up (path dependence). Many actions are irreversible.

- *Self-organizing:* The dynamics of systems arise spontaneously from their internal structure, generating patterns in space and time and creating path dependence.

- *Adaptive:* The capabilities and decision rules of the agents in complex systems change over time. Evolution leads to selection and proliferation of some agents while others become extinct. Adaption also occurs as people learn from experience.

- *Counterintuitive:* In complex systems cause and effect are distant in time and space while we tend to look for causes near the events we seek to explain. Our attention is drawn to the symptoms of difficulty rather than the underlying cause. High leverage policies are often not obvious.

- *Policy resistant:* The complexity of the systems in which we are embedded overwhelms our ability to understand them. The result: Many seemingly obvious solutions to problems fail or actually worsen the situation.

- *Characterised by trade-offs:* Time delays in feedback channels mean the long-run response of a system to an intervention is often different from its short-run response. High leverage policies often cause worse-before-better behaviour, while low leverage policies often generate transitory improvement before the problem grows worse.

3.3.3 Mental Models

Complex problems are not just physical regularities that enable reduction of physical phenomena. Further, when human activity is included difficulties in separating it from its physical surroundings make it hard to define what to include or exclude (Checkland 1988). The complexity with human activity on problems is that it is not the problems that appear to the

problem-owners but their perception of the problems (Checkland 1988). A problem in manufacturing may therefore be interpreted in various ways.

The phenomenon, of different interpretations by different people, is termed "mental models" in system dynamics literature (Forrester 1961; Senge 1990; Doyle and Ford 1998; Sterman 2000; Maani and Cavana 2007; Morecroft 2007). The definitions vary but the concept is as previously described. That is, mental models are inner simplifications and models inside people's heads to interpret the surrounding environment and phenomena. They can be simple or advanced depending on experience. They are unchangeable until willingness occurs to learn. And, they guide people's actions. For manufacturing systems development revealing and approaching one another's mental models of problems could bring opportunities for operative solutions.

3.3.4 Social Reality

Social reality is a term that tries to describe the complexity of reality in which individuals interact. It is in this environment a system dynamist tries to interpret and model. For this thesis the environment could be exchanged with the manufacturing system that is studied. See figure 3 below. How the social reality affects the behaviour of systems can be put in summary as:

- "If men define situations as real, they are real in their consequences" "the Thomas theorem" in (Vennix 1996)

- The consequences of people having an expectation in a certain situation lead to a behaviour that produces the expectation. Phenomenon known as self-fulfilling prophecy.

- The behaviour of self-fulfilling prophecies is reinforced by that people tend to have selective perception and look for confirmations of viewpoints, instead of facing refuting evidence.

- It can also result in the self-denying prophecy. An example of a degenerating prophecy is: people's reaction to employment forecasts for a certain branch that says that it will be full in a few years. But instead, this forecast will result in a lack of professionals, since students listened to the warnings of future unemployment in that certain branch.

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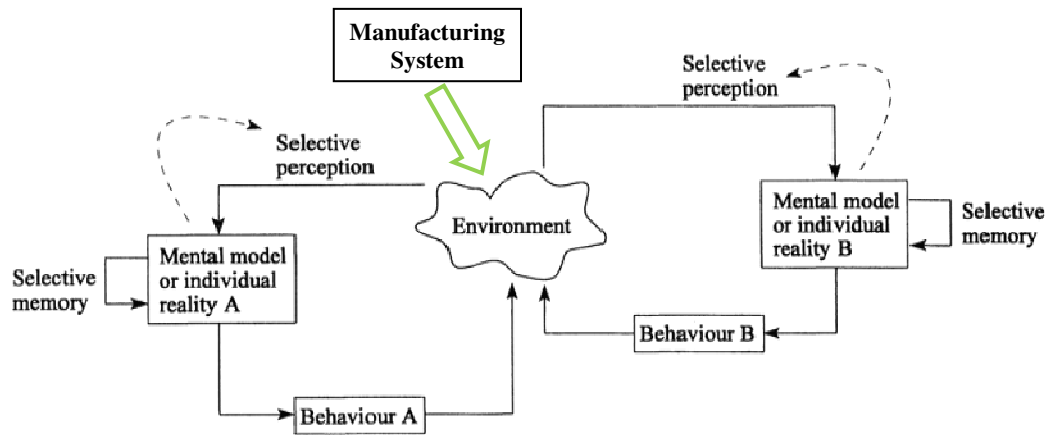
Figure 3   The Creation of Reality (Vennix 1996), complemented with the studied Manufacturing System as the Environment

Figure 3, is a model simplification by Vennix (1996), of how the common reality is created from human interaction. Model explanation: Individual "A" carries an individual model of reality, and applies selective memory, he/she selectively percept the environment (manufacturing system) based on previous experience; altogether resulting in "A's" behaviour. The same procedure is for individual "B" whom interacts with "A" in a common environment. This fairly simple model only considers a few elements of the complexity of human systems. And it shows that human interaction becomes messy and dynamic with only a few actors.

It can be noted that these aspects are vital for manufacturing systems development. In order to make smart decisions the basis for change has to be correct. Applying a method that uses the language of systems and acknowledges the social aspects of system behaviour should reasonably facilitate a better informed basis for change.

3.4 MODELLING

The first three sections in this chapter can be categorised as those aspects necessary for generating basic understanding for modelling. And the three latter sections can be categorised as those aspects important for the contribution of this thesis, putting modelling in the wider perspective.

- The Building Blocks of Modelling
- Qualitative or Quantitative Modelling

- The Modelling Process
- Understanding Model Behaviour
- Group Model Building
- On Descriptions of Modelling in System Dynamics Projects

3.4.1 The Building Blocks of Modelling

The body of building blocks in modelling shows how the hierarchies in the theory of structure section (3.3.1) are represented in modelling. The building blocks are few in system dynamics. A model is comprised of only Levels and Rates. Levels are also referred to as *Stocks,* and Rates are also referred to as *Flows.* Levels can only be affected by its connected Rates (there can be several in and out flows). Rates are ruled either by another rate or most commonly by Rate Equations. Rate Equations are comprised of Auxiliaries and Constants. Another fundamental component is Time and the size of each Time Step a simulation run, which depends on the modelled problem.
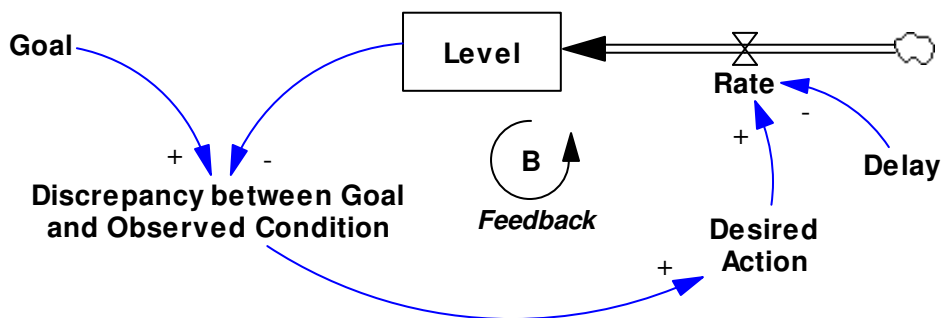

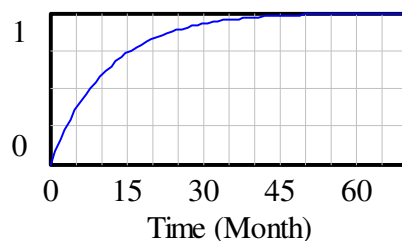*Figure 4   Goal oriented Balancing Feedback loop comprised of Level, Rate, Auxiliaries, and Constants*

Figure 4   Example of Behaviour Graph for Level in figure 4

$$Level\ (t) =\ Level\ (t - dt) +\ Rate\ \cdot dt \qquad\qquad \text{(Equation 1)}$$

$$Rate = \frac{Desired\ Action}{Delay} = \frac{Discrepancy\ between\ Goal\ and\ Observed\ Condition}{Delay} =$$

$$= \frac{(Goal - Level)}{Delay} \qquad\qquad \text{(Equation 2)}$$

Level (1) and Rate (2) equations:

(1) The Rate accumulates into the Level in each Time Step (*dt*)

(2) The equation is the consequence of defined policies and present Level

Combining Equation (1) and (2) results in feedback between the parameters. The "B" in figure 4 means that it is balancing feedback that governs the loop, and the counter arrow shows its direction. The building blocks, described by figure 4 and explained by equations (1) and (2), are the tools to map the feedback loops of a system. Feedback loops are the structural elements of systems (Forrester 1968) and elementary in decision making. A system most often comprises several feedback loops, and they are central to dynamic modelling. The physics of Levels and Rates are: a Level equals the same properties as a state of a system, if time stops it has an accumulated value; a Rate equals the same properties as a flow, if time stops it has no value.

Figure 4 explicitly shows that the defined hierarchies mentioned previously are all included in the Rate equation (2). For a more complex system, it requires an explicit overview in order to enable a readable model. The added explicit variables, are termed Auxiliaries, and are typical to include for a pedagogical reason. An Auxiliary explicitly shows that it exist a mathematical relation of those variables that are connected to it. Figure 4 also represents a *Delay* and a *Goal*; they are Constants and are not affected by any other variable. This means that how any Constant is set is not regulated by any other parameter. A Constant is by this definition a variable that represents a boundary in a model. Another aspect of model boundary is represented by the cloud in the rear of the Rate arrow. The flow into the Level is not draining any other Level which consequently is excluded from model boundary.

3.4.2 Qualitative or Quantitative Modelling

Both qualitative and quantitative modelling is used in system dynamics, but there is a standpoint that quantification has a decisive importance for a thorough study (Forrester 1970; Richardson 1996; Homer and Oliva 2001). The qualitative procedure termed *systems thinking* was popularised by Senge (1990) and has been used since the early 1980s (Coyle 2000).

Guidelines on whether to apply qualitative or quantitative modelling are identified as a problem for the field to address; "when to map and when to model" (Richardson 1996, p 8). This thesis suggests using quantitative modelling in the presented *framework,* in *Findings.* The reasons for that are: enabling experimentation of a modelled manufacturing system, which is desirable (Case C); and without using simulation it is near impossible to understand a system's nonlinear dynamics (Forrester 1987).

The two figures 5 and 6 below show (explain) the same system. But figure 5 is a qualitative model and figure 6 is a quantitative model.
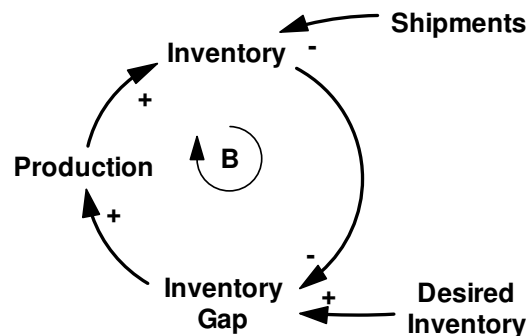

Figure 5   A qualitative model of an Inventory policy, from (Repenning 2008a)
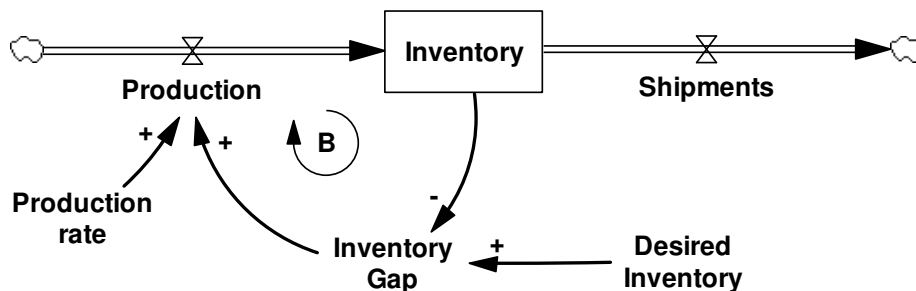

Figure 6   A quantitative stock and flow model of the same system as in figure 5

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The causal structure is the same in both figures: *Shipments* drain *Inventory*, the difference between the *Desired Inventory* level and the real *Inventory* level is the *Inventory Gap,* which size defines the capacity of *Production,* filling up the *Inventory* again. In order to enable simulation there is another variable constant termed *Production rate* in figure 6.

The two modelling techniques use the same basis regarding:

- *causal structure:* the interrelatedness of system components

- *feedback thinking:* how action affects results and how these results affect decision for action, resulting in further direction for action

- *qualitative analysis:* mentally performed simulation

Quantitative modelling brings further:

- *variable characteristics:* which describes the interrelatedness of system components (stocks, flows, and constants) in form of equations

- *enables simulation:* through computing defined equations and providing an experimenting model

The balancing loop (B) balances the level of *Inventory* to a certain goal value. The behaviour of feedbacks may be simple to tell in this model; however, in more complex structures it can be difficult to intuitively judge the total behaviour. Therefore each feedback loop is defined using some basic rules:

- *Causality*: the '+' or '-' sign shows how the relation is. For example, in figure 5, when *Shipments* goes up *Inventory* goes down is resulting in a '-' (opposite direction). In the same procedure a '+' means an effect in the same direction.

- *Defining feedback loops:* Either a loop is balancing or reinforcing, it depends on all variables' relations in that loop. Practically you start in any of the variables of a loop and use the previous rules. Start on a variable in the loop with either, 'goes up' or 'goes down', walk through the loop in order to determine how the variable affects itself. If it is affecting itself in the same direction as the starting direction it is a reinforcing feedback loop, otherwise balancing.

Qualitative *systems thinking* is applied as a tool for:

- analysing a problem or system structure in order to provide with organisational learning (Senge 1990)

- analysing which future choices of organisational development that are most applicable (Vennix 1996)

- facilitating the analysis of a system in the starting phase of a system dynamics modelling project (Repenning 2008a)

- presenting a system dynamics model in a more communicative procedure for an audience in order to avoid getting into unnecessary details (Homer and Oliva 2001)

Quantitative system dynamics add to this:

- a dynamic presentation of the modelled system facilitating understanding of problem causes (Sterman 2000)

- the possibility to experiment on different possible scenarios in order to explore how to perform change (Morecroft 2007)

These different properties indicate on different use depending on which approach that is applied. *Systems thinking* can provide with a satisfying analysis for change (Senge 1990; Vennix 1996; Sterman 2000; Maani and Cavana 2007; Morecroft 2007). Coyle (2000) brings it further and states that a qualitative analysis is enough, especially dealing with uncertainty, further, that a quantitative analysis needs more time bringing more cost than value. Homer and Oliva (2001) claim this to be incorrect saying that quantitative modelling provides with a more thorough analysis. And, that simulation brings increased possibility to test if uncertainty is affecting the system. And, that simulation facilitates judging if enough data exists to reach correct conclusions. A system dynamics model provides testing (validation) of the assumptions about the interacting element's relations. A *systems thinking* model provides only qualitative evaluation on validity.

3.4.3 The Modelling Process

The modelling process is highly intuitive and unique for every modelling project (Sterman 2000). However, there are steps in modelling that are

general and generic. In literature these steps range from articulating problem phenomena to implementing (Forrester 1961; Forrester 1994; Vennix 1996; Maani and Cavana 2007). Figure 8 below is a five step modelling process. It shows how the modelling process interacts with the surrounding environment (social reality). The iterative process of modelling is illustrated using a web picturing a star in the middle of the figure, representing that each step may have consequence on the other. For example, an unexpected *testing* result may lead to refinement of the *problem articulation* or *dynamic hypothesis*. Sterman's (2000) model of this process further includes *information feedback* from the *real world* from the *organisational experiments* that came out from modelling, indicating on a continuous movement.
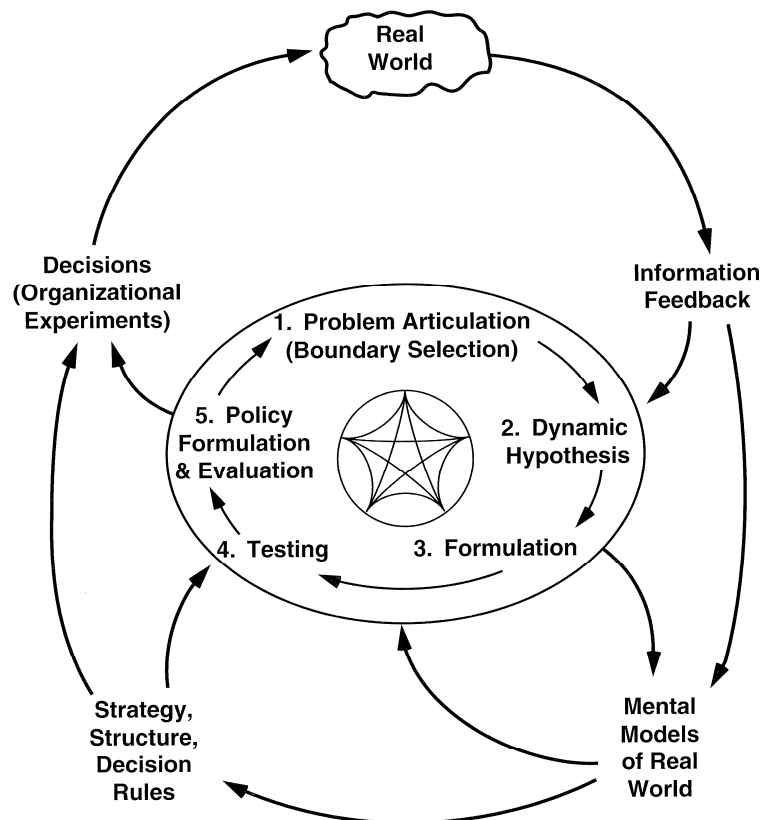

Figure 8   The iterative modelling process in system dynamics (Sterman 2000)

The key aspects in the 5 steps of the modelling process are reviewed in brief, from (Sterman 2000, p 86):

1. *Problem articulation:* sets the boundary selection which answers to: what is the problem; why is it a problem; what are the key variables to consider; what is the time horizon of the problem – past and future; and how are the dynamic reference modes of the past and how might it be in future?

2. *Dynamic hypothesis:* perform an initial hypothesis based on current theories of the problematic behaviour; formulate a dynamic hypothesis of how the problem dynamics is endogenously generated from the feedback structure; map a causal structure based on the inputs to step 1.

3. *Formulation:* develop a simulation model in order to test the dynamic hypothesis, it includes: specification of structure and decision rules; estimation of parameters, behavioural relationships, and initial conditions; tests for consistency with the purpose and boundary.

4. *Testing:* validation (chapter 3.5); "does the model reproduce the problem behaviour adequately for your purpose?"

5. *Policy formulation and evaluation:* scenario specifications; how can new policies be designed; "what if" analysis from policies; sensitivity analysis of suggested policy recommendations; examine if there is any interaction of policies that may lead to synergy effects.

3.4.4 Understanding Model Behaviour

Understanding model behaviour is one of the identified problems for the system dynamics field to address (Richardson 1996). Understanding is important for enabling utilisation of a change support thus essential to approach in this thesis. In a wider perspective understanding can be divided into three dimensions:

1. Understanding a real-system, in order how to formalise it into a model (Forrester 1994)

2. Understanding a model of a system (Warren 2005)

3. Understanding of model behaviour (Richardson 1996; Warren 2004)

Lack of support for item number one has been stated (Forrester 1994). To improve it suggestions have regarded: *operational thinking* which focuses

on key arrangements of stocks and flows forming the infrastructure of a system (Richmond 1994); and *feedback loop thinking* which focuses on identifying the reinforcing loops in the system and then those balancing loops that limit growth (Repenning 2008a). Richmond (1994) argues that using *feedback loop thinking* as an initial tool for approaching a system may instead make it harder, causing a "laundry list thinking" of factors. Akkermans (1995) is defining suitability of both approaches, but for different uses calling them: process flow orientation and causal network orientation respectively.

Improvements for item number two have regarded: visual simplifications termed sector maps and space-compression objects (Richmond 1994); and including structure and feedback-behaviours-graphs of each variable in the same picture (Warren 2005). Richmond (1994) agrees that *feedback loop thinking* could serve its purpose in explaining a model "after the fact" (dissemination), similar to the view of Forrester (1994).

Less work has been done to improve item number three. Which is described as "The principal outstanding technical problem in simulation modeling is the development of tools to aid understanding model behavior." (Richardson 1996, p 11) A software support is argued for in order to understand how the stock and flow feedback structures of a system are linked to its behaviour. However development of such software has not been found described in literature. Understanding behaviour is difficult and is hopefully the outcome from the traditional procedure; a time-consuming operation of iteratively constructing understanding of a system's behaviour through "formulation to parameterization, testing, observation, hypothesizing and back again" (Richardson 1996, p 2). However, Warren (2005) claims his method strategy dynamics (Warren 2002) to improve on this matter. Warren (2005) argues that system dynamics has theoretical, pedagogical, and managerial flaws and that they have caused the non existence of the method in the top-fifty-list of applied management tools. Presenting models including structure together with feedback-behaviours-graphs is argued to counteract these flaws, facilitating understanding of model behaviour.

This thesis' attention, to this problem area, is on the level of suggesting on path for usage of existing methods, such as: *operational thinking* in order to

formalise a model, group model building as a mean to facilitate understanding of the constructed model, and for understanding model behaviour it has to rely on the traditional procedure previously described. Hence, this thesis excludes any new development in this area, neither suggest suitable modelling software; it is outside the delimitation.

3.4.5 Group Model Building

Group model building has a clear point of contact with the core of this thesis. It uses an approach to managerial modelling (Lane 1994; Akkermans 1995) that focuses on learning through including the client in the model building, suitable for business improvements in manufacturing. Shared understanding among group members is the desired effect, enhancing the results from modelling and thereto improving the conditions for implementation of solution (Lane 1994; Andersen et al 1997; Vennix 1996). The primary goal of group model building is to engage people "in building a system dynamics model of a problem in order to see to what extent this process might be helpful to increase problem understanding and to devise courses of action to which team members will feel committed" (Vennix 1996, p3). A study of 107 cases (Rouwette et al 2002) shows that group model building has an impact on client organisations. However, the area of group model building is rather recent, and it is still developing (Andersen et al 1997; Rouwette et al 2002). The two most important issues for the future are the need of a more consistent theoretical framework and more extensive empirical research on its effectiveness (Rouwette and Vennix 2006).

Grössler (2007) brings up the research problem that: system dynamics projects tend to suffer from failing to make an impact, despite their positive outcome both in academia and companies. He suggests "an increased embedding of system dynamics projects in organizational intervention architectures" (Grössler 2007) in order to improve the level of impact from modelling. This thesis suggests including experts and leaders in direct contact with the problem in a modelling project for increasing commitment and in order to facilitate dissemination of results into the organisation (Case B). It is in line with the requirements on good client participation and high client ownership, identified truly crucial by Akkermans and Bertrand (1997). Moreover it includes those people on the level of the problem's concern; the operational management in manufacturing. And

acknowledging this opportunity has a base in the identified cure for improving the missing link in manufacturing by Skinner (1969); that top management actively would manage manufacturing through the making of policies. These aspects in total may support preventing the development identified by Grössler (2007).

Figure 9 shows the choices when designing group model building projects, from (Vennix 1996).

Client organization experiencing problem

Relevant questions:
-is the problem dynamically complex?
-short-term-long-term effects?
-reference mode of behaviour?
-qualitative or quantitative model?
-who to involve?

Is system dynamics appropriate? — No — Look for alternative methodology

Yes

Use preliminary model?

Yes — Preliminary model based on

No — Start from scratch

Documents — Interviews

(Interviews e.g. to build rapport)

Questionnaires/ workbooks for participants

Group model-building session(s)

Group model-building session(s)

Group model-building session(s)
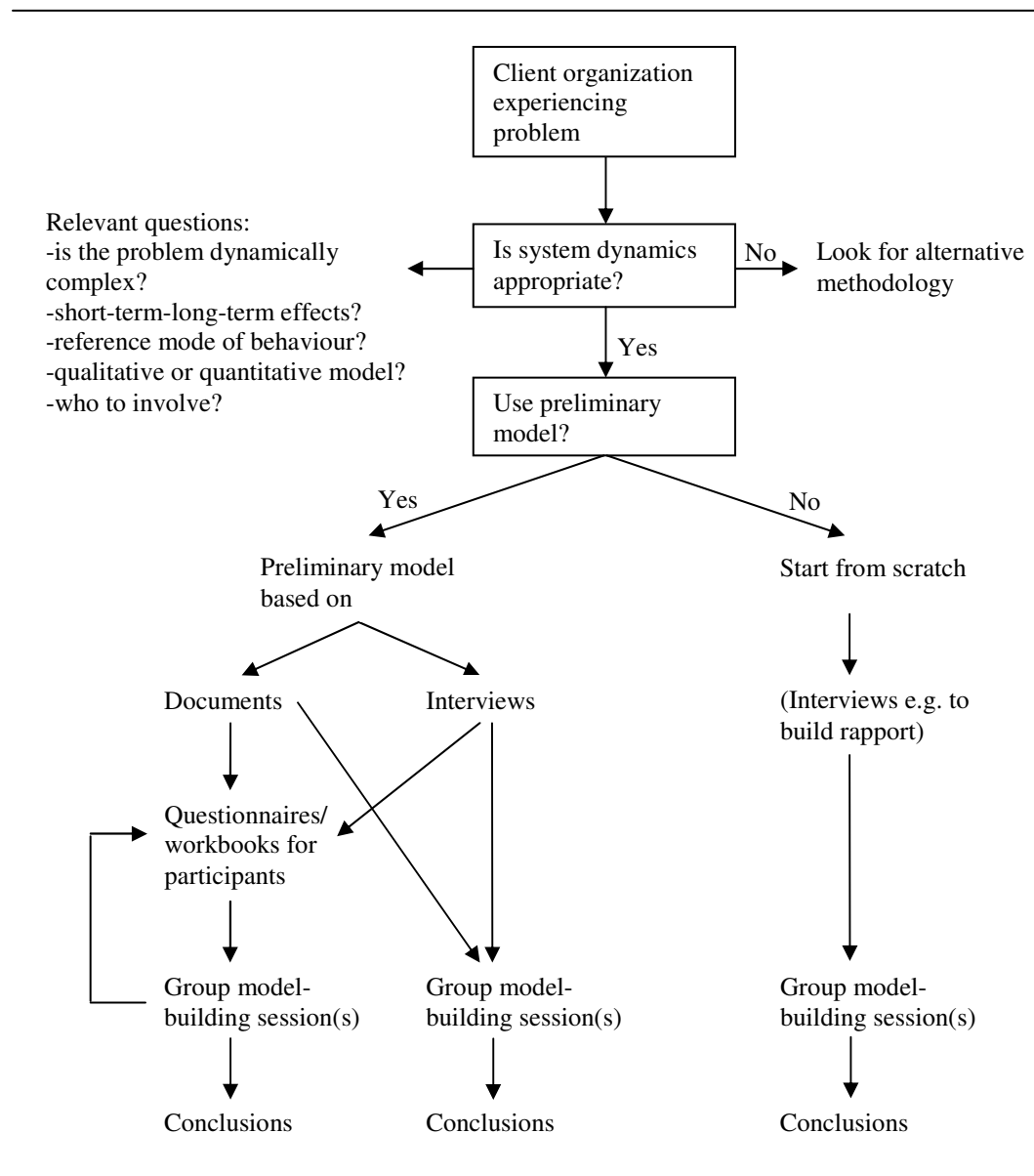
Conclusions

Conclusions

Conclusions

Figure 9   *Illustration of choices in designing projects (Vennix 1996, p 103)*

Each sequence of how to design a modelling project is shortly introduced:

- *Is system dynamics appropriate:* Firstly, the conclusion if system dynamics is the proper methodology to use has to be drawn.

  o *Relevant questions:* Three questions guide appropriateness: if the problem is dynamically complex or not is central to the evaluation; if there are time dependent effects from change indicate feedback relations; and if there are any identified reference modes of behaviour enable creating a perception of the past evolvement of the problem. Depending on problem characteristic and budget the project is suggested to use either a qualitative or a quantitative approach. Who to involve: a rule of thumb in group model building is to include those who have the power to act and those important for enabling commitment with the final decision in the organisation.

- *Use preliminary model:* Using it or not depends on the experience of the modeller/modelling team and the time and budget. Using it enables a faster project and a more convenient situation for the non-experienced modeller, whereas model building can be performed mainly meantime modelling sessions. Using it may weaken the commitment and thus the conclusions brought by the project.

- *Preliminary model based on, Documents or Interviews:* The choice depends on the problem character, if there are available documents, and the amount of available time of those included in the project. Whatever the choice, a preliminary model has the objective of providing the first modelling session with a model to criticise and adapt to the mental models of the modelling group.

- *Questionnaires/ workbooks for participants:* Depending on geographical location, time budget, or if the subject of modelling is politically sensitive it can be appropriate to elicit information individually from the participants in between the modelling sessions. This is performed by asking questions in a format of a workbook handed out to the group participants. It facilitates getting on with modelling. This can be performed between each session or when needed.

- *Start from scratch:* Not using a preliminary model requires that the modelling process is performed by heart. It requires substantial art in

performance from the modeller since interviews for collecting data is gained during the model building session.

- *Group model-building sessions:* Vennix (1996) brings up the different roles of use in a modelling team; whereas facilitator and recorder combined with a gatekeeper is most important and proposed as a minimum team. The facilitator has the utmost important task to use his skills in order to read the group and act thereafter in order to get progress going. It is also of importance to make clear beforehand the purpose and expected outcome of a session. During the session: check the group's experience of system dynamics; assure consensus on what problem to model; make expectations clear; cycle back and forth between problem and the model of it; plan breaks; and record conclusions and insights. The results of a session could be evaluated by the amount of data brought into the model, however: "It is more important that people have the feeling that the session was worthwhile, because they all got a chance to voice their ideas" Vennix (1996).

- *Conclusions:* Are drawn upon the achieved results, did the modelling provide with answers to the set out objectives? At this point the aspect of validation has a natural part, as well as during modelling.

3.4.6 Descriptions of how to Implement System Dynamics Projects

The access to system dynamics project descriptions is limited; no guidelines for a complete project exist and present guidance in literature is provided in isolated parts. The support available is descriptions of the modelling process from identifying a problem to policy changes. However, those guidelines accessible are limited to brief modelling process descriptions, nevertheless provided in numerous literatures (Forrester 1961; Richardson and Pugh 1981; Forrester 1994; Vennix et al 1994; Sterman 2000; Maani and Cavana 2007; Morecroft 2007). Out of these it is found that the description in Sterman (2000) is most thorough, shown previously in figure 8. In e-mail contact with Nelson Repenning, faculty at the *Executive Education Program in Business Dynamics MIT's Approach to Diagnosing and Solving Complex Problems,* he was asked if there were any more specific modelling process descriptions than the one provided in Sterman (2000); which uses 20 pages out of total 1000 for this purpose. His answer underlined that the best description so far was that by Sterman (2000). And

he further referred to that: "for better or worse, modeling remains a mixture of art and science and both parts take practice to cultivate" (Repenning 2008b).

Common in all these descriptions of a system dynamics project is their level of focus. It is generally on the level of reviewing the steps of the modelling process. Sterman (2000) goes a bit further than the others in his explanation of how the modelling process interacts with its environment. None of these descriptions include guidelines how to carry out the *implementation* of a system dynamics project. However, in his book Vennix (1996) shows how to carry out a group model building project, which complements some lacking parts on *implementation* of a project. Although, Vennix (1996) state that even if his book is a 'how to do' support, it is required that you posses skills in model building, only gained through extensive training.

In conclusion mainstream literature restrict to presenting the steps of modelling (Forrester 1961; Richardson and Pugh 1981; Forrester 1994; Vennix et al 1994; Sterman 2000; Maani and Cavana 2007; Morecroft 2007), perhaps satisfying for academic purposes and theory building (Schwaninger and Hamann 2005). Although, group model building (Vennix 1996; Andersen et al 1997; Rouwette et al 2002; Luna-Reyes et al 2006; Rouwette and Vennix 2006) and more specifically modelling for managers (Akkermans 1995; Lane 1994) show how modelling can be performed when interacting with the practical world, it is not guiding a complete project. It is identified that in order to bridge the gap between theory of using system dynamics and its practice in a manufacturing environment, a *framework* of guidelines is needed. A *framework* that comprehend necessary elements for a system dynamics project from: introduction of the theoretical base, to support implementation.

3.5 VALIDATION OF MODELS

Validation builds confidence about how correct a model mirrors a system. Confidence and validation is a problem area (Richardson 1996). "What are appropriate procedures and standards for establishing user confidence in system dynamics models in various decision environments?" (Richardson 1996, p 11). Barlas (1996) presented a general framework for identifying

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proper validation criteria depending on type of model. His framework is used when describing model validation in this thesis.

In modelling and simulation validation is a procedure of model testing. The purpose of a model has the strongest impact on how validation is carried out. All tests are carried out with the model's purpose in mind. Another crucial aspect regarding validation is that actually all models are wrong, because "all models, mental or formal, are limited, simplified representations of the real world" (Sterman 2000, p 846). Finally, validation is a matter of acceptance of the results, however excellent the tests are passed, without acceptance that score does not matter. This has a clear connection to model ownership, important for acceptance of model results.

3.5.1 Validation Methods

In the framework, by Yaman Barlas (1996) in figure 7, the purpose is to explicitly show that validation can be divided into three main types of tests:

1. *Direct structure tests:* Do not use simulation and compare model with knowledge about the real system; information from the system (empirical) and from generalised knowledge (theoretical).

2. *Structure-oriented behaviour tests:* Use simulation in order to study the behavioural results as a mean to indirectly find out structural flaws.

3. *Behaviour pattern tests:* Result in a measure of model accuracy in reproducing the behaviour patterns found in the real system.
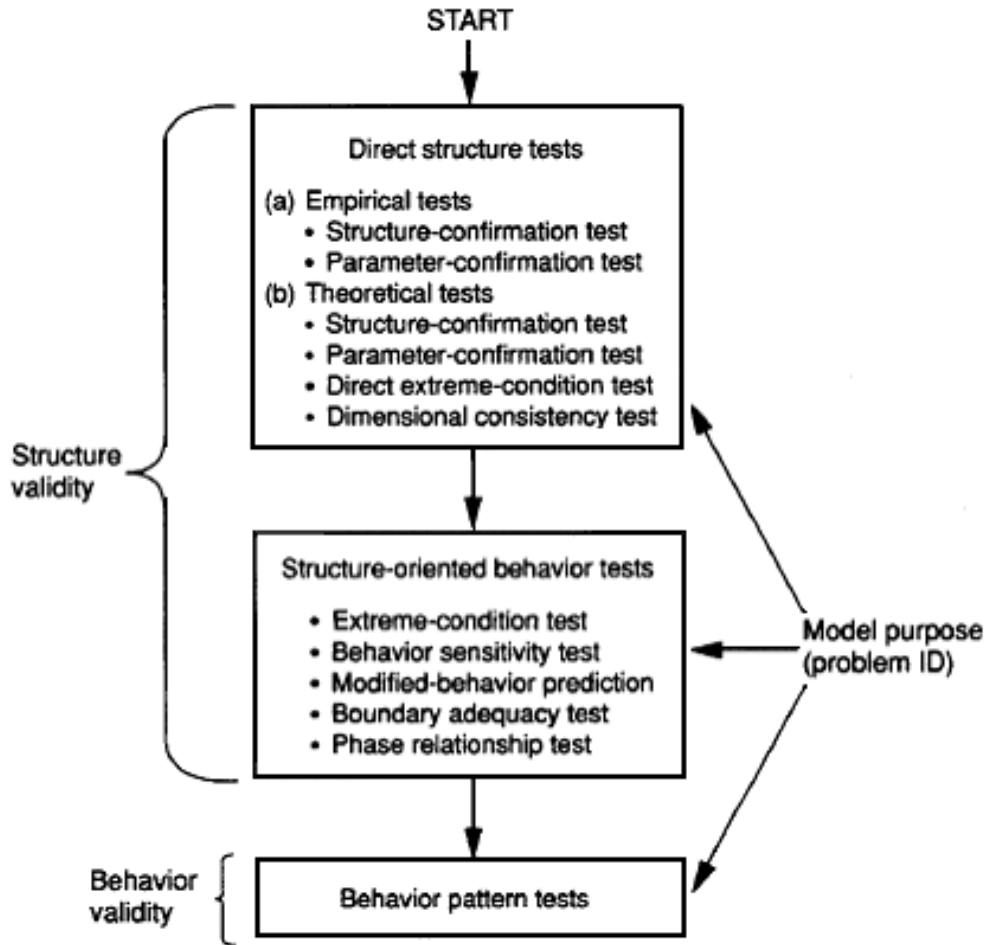
Figure 7   *"Overall nature and selected tests of formal model validation",*
            modified from (Barlas 1996).

1. Direct structure tests

- *Structure-confirmation test:* Comparing of model relations (equations) with existing relationships in the real system (empirical) and with generalised knowledge in the literature (theoretical). One of the most difficult tests to formalise and quantify (Barlas 1996). It is based on qualitative data, the interpretation of how the real system is functioning.

- *Parameter-confirmation test:* Evaluation of how the constants in the model agree to the real system, either empirically or theoretically.

- *Direct extreme-condition test:* Evaluation of each equation in order to avoid incorrect results; for example, a negative inventory value should not be possible.

- *Dimensional consistency test:* Each equation should be dimensionally consistent on both left-hand side and right-hand side of an equation.

2. Structure-oriented behaviour tests

- *Extreme-condition test:* Assures that the model achieve similar behaviour in an extreme condition as the real system would do.

- *Behaviour sensitivity test:* Locates those parameters highly sensitive for model behaviour, and evaluates if the real system would behave in a similar procedure.

- *Modified-behaviour prediction:* This can only be performed if historical data of a modification of the real system exists. Then, the model can be tested applying the same structural modifications as in the real system, and produces a pass if similarities in results are achieved.

- *Boundary adequacy test:* With the purpose in mind; are the important aspects of the problem behaviour included in the model? If the model behaviour changes significantly when the boundary is modified it needs to include these changes. Consequently if the behaviour is unaffected from a boundary change it may be excluded. Further, as far as possible modify exogenous variables and constants in the model into endogenously generated ones.

- *Phase relationship test:* Some pairs of variables may show a similar behaviour in a model, this test examines if the same phase relationship exists in the real system. Correspondingly a phase relationship in the real system should be shown by the model.

3. Behaviour pattern tests

- *The emphasis of* system dynamics models is on pattern prediction (such as "periods, frequencies, trends, phase lags, amplitudes, …" (Barlas 1996)), not on event prediction. However, behaviour pattern tests do not provide any added value on the validity of a model structure.

Sterman (2000) presents the steps of validation in his book without the categorisation of Barlas (1996) above. The steps are in line with Barlas' (1996) presentation, but Sterman (2000) provides the tests listed in another

logical order. It is in relation to the model purpose; starting at boundary adequacy and ending in system improvement. Case study C thoroughly describes how it used the validation aspects in Sterman (2000).

3.5.2 Validation Requirements Depending on Type of Model

There are some different uses of system dynamics models, and their requirements on validation are different. These are divided into:

- Modelling of a real system in order to achieve improved performance (Forrester 1961; Sterman 2000); uses all three stages of validation tests described above (Barlas 1996).

- Modelling of an existing theory in order to test it or to improve it (Schwaninger and Hamann 2005); uses the two first structural tests but has typically no use of the third (Barlas 1996).

- "Management flight simulators" (Sterman 2000) is a more recent application within the field, and in building the simulator model all three stages of the validation test is desirable but may require other disciplines as well, such as cognitive psychology, information systems design and computer technology (Barlas 1996).

- Modelling for learning (Lane 1994), using group model building (Vennix 1996) is also quite recent within the field. Mainly t uses the two first structural validation tests since the purpose is learning oriented and holds similarities to models of scientific theories (Barlas 1996).

3.6 SUMMARY ON SYSTEM DYNAMICS

System dynamics is a systemic approach that both explains the "universal structure of real social and physical systems" (Forrester 1994, p 13) and guides the construct of a model of a unique system for analysis. This makes it suitable for manufacturing systems development on the system level in focus of this thesis. It also shows that quantitative modelling is more suitable than qualitative modelling. Because it provides a tool that is able to dynamically present the modelled system's behaviour and enable experimentation for improvements.

The modelling process in system dynamics has an iterative character, between model and the social reality it aim to model. For this thesis it is the social reality of the manufacturing system that is under study. Group model building is identified as a suitable type of use for manufacturing systems development due to its ability to facilitate the conditions for implementation of solution. Using group model building for manufacturing systems development may also acknowledge the missing link in manufacturing identified by Skinner (1969), that management actively would manage manufacturing through the making of policies.

The state of the art modelling supports are identified; however their level of focus is on a general level. How to implement a system dynamics project in reality is not covered. It may be satisfying for academic purposes in theoretical cases but not on the level required for manufacturing systems development. In total it is this that has become the focus of contribution of this thesis. Thus the findings chapter describes a framework of guidelines, how a support for system dynamics projects could be packaged for manufacturing systems development.

Validation of models follows certain tests in order to build user confidence. Applying group model building involves the client into the modelling process, creating understanding from problem to solution. Altogether it may increase level of acceptance for model results; reinforcing validation of a model and dissemination into the organisation.

4 FINDINGS

4.1 CASE STUDIES

Three case studies of different character, performed in manufacturing industry, are included in the thesis:

Case A – Industrial Case

Shows the potential use of system dynamics in a modelling case, explores difficulties that widen the gap between theory and practice for manufacturing systems development, and identifies the need of using group model building as a potential to increase commitment for results.

Case B – Theoretical Case

Connects change management with system dynamics, defines the level of change, indicates how group model building may facilitate the drive of change and suggest further examination, and it includes a cost model based on a real-world situation.

Case C – Group Model Building Case

Identifies group model building as a requirement for using system dynamics in manufacturing, shows further need of increasing commitment for using model results, suggests more time for experimenting and better support.

4.1.1 Industrial Case

Case A: Cutting Tool Management: A Dynamic Assessment of Opportunities for Improvement (Linnéusson et al 2008)

The case explored applying system dynamics for solving a management problem in a manufacturing industry context. A system dynamics simulation model of a cutting tool management situation at a manufacturer

was constructed. Focus for modelling was: how a tool data management system may implicate on cutting tool management performance.

The case showed that system dynamics can be applied for investigating a problem situation in this context. Using system dynamics for studying cutting tool management is novel, not previously described in literature. The study confirmed motivating using system dynamics for achieving the objectives (chapter 2.1). Case A was a successful test of usability, but required much creativity. The modelling description in figure 11 was used, and information from literature (Forrester 2002; Maani and Cavana 2007; Morecroft 2007). A support for performing simulation projects in manufacturing could not be identified and the other descriptions were lacking, resulting in a modelling process characterised by trial and error.
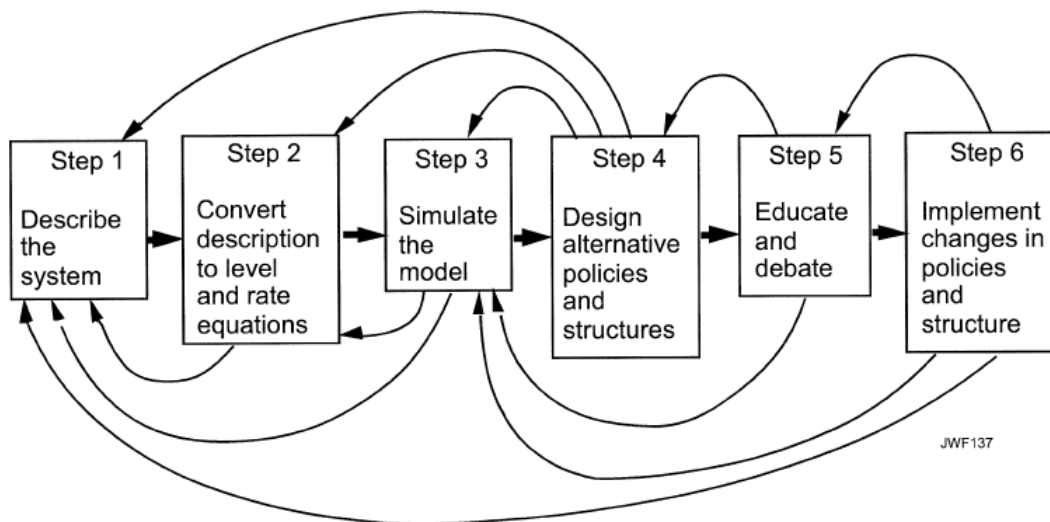
Figure 11   System dynamics steps, from (Forrester 1994)

Conclusions from the case study: for better commitment future research must focus on group model building; the main use of system dynamics was the extended view it brought. The extended view included locating the root cause for problem behaviour and increased understanding for solving it.

The method to obtain the results used:

- *System dynamics*: modelling and simulation of a present situation and a future state

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- *Data collection*: a cutting tool management literature review and informal interviews with people in the system

The ordinary system dynamics approach was used; similar to the term "expert consultancy" (Lane 1994). The iterative modelling process used: reviewing literature, interviews, and modelling. One consequence from the "expert consultancy" approach is that modelling is the result of the modeller's interpretation of the real system. Consequently the client, or the owner of the problem, has to be persuaded by these findings later in separation to the model building process.

Figure 12   "After the fact" model of the Case Study results

Figure 12 shows the feedback structure using qualitative modelling, used in conference proceedings for presenting the results.
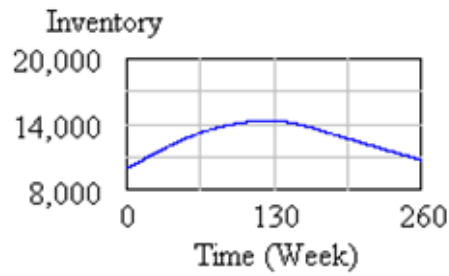
Figure 13   Results from implementing a tool data management system

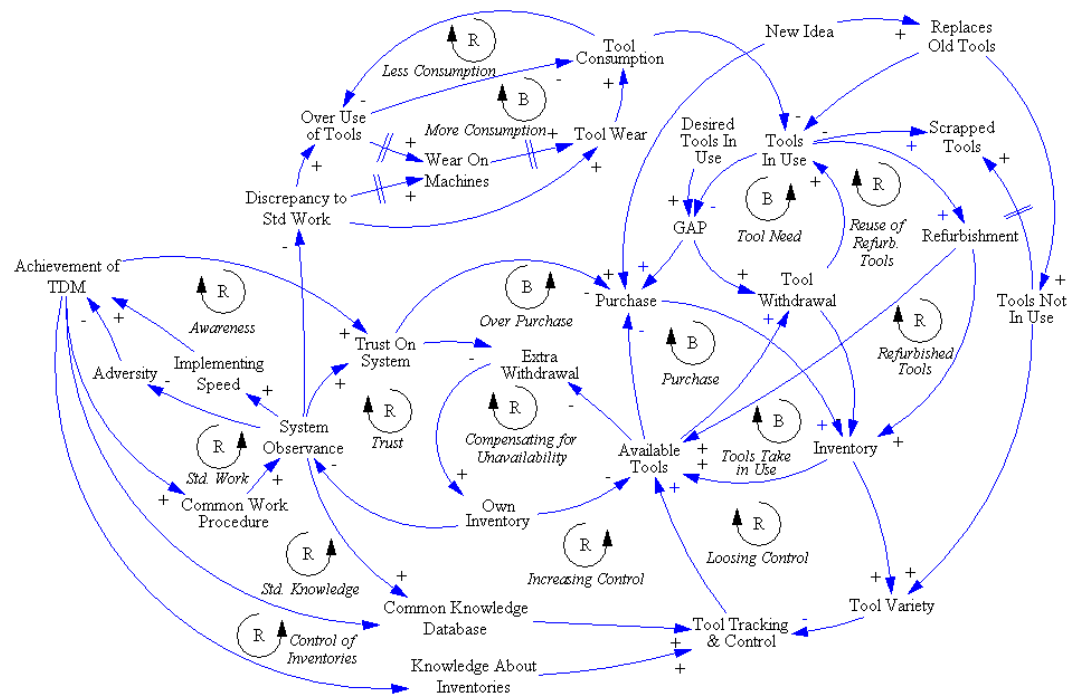Figure 13, the results from simulation show that implementing a tool data management system will improve the present system, however after some years delay. Initially, inventory continues to grow but after near three years starts to decrease. Simulation brings the advantage of analysing how the experienced behaviour is generated in the system.

4.1.2 Theoretical Case

Case B: On Applying a Systems Approach to Manage Operative Improvements in Manufacturing (Linnéusson and Jägstam 2008)

Case B shows that a systems approach can be fruitful to combine with change management in order to manage operative improvements in manufacturing. System dynamics group model building is considered facilitating "the drive of change" (Beer 2001) in manufacturing organisations. This as a complement to current mainstream event- and equipment- oriented business improvements.

The method to obtain the results used:

- *System dynamics*: modelling and simulation for experimenting on changes in a real-world case, using a cost model

- *Data collection*: informal interviews; literature surveys of change management, complexity of change, and systems thinking

- *Theory development*: definition of research project area

The survey indicated suitability of using system dynamics for change management. The most powerful approach to organisational change is the combination of economical driven change and organisational capability

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changes (Beer 2001); a combined top down and bottom up driven change. Using system dynamics group model building was judged, on a theoretical level, to be able to support this combination. The benefits are the feedback systems thinking, facilitating holistic learning within the project group, and experimentation for change.
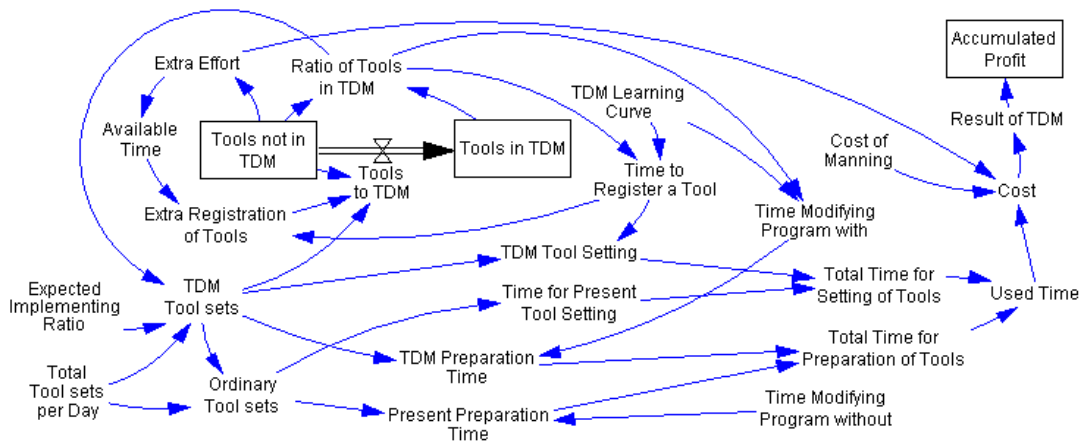
Figure 14   Cost model of implementing a tool data management system

Figure 14, a cost model that can be used for testing outcomes from different change strategies. This model serve a similar purpose to an excel sheet, commonly used in manufacturing for calculating on change. Using a cost model brings deeper enlightenment to the change process, providing dynamic scenarios from different strategies. Further it can include dynamic elements, such as learning, which is difficult in a static excel sheet.

4.1.3 Group Model Building Case

Case C: Machine Strategy Evaluation Using Group Model Building in System Dynamics (Linnéusson and Jägstam)

Case C was a group model building project to explore its usage in a manufacturing context. The aim with the project was to increase understanding of how to achieve a rewarding machine strategy. The case study was to answer three research questions, in concise descriptions:

RQ1.   Do participants consider themselves to have reached learning of the studied system?

RQ2. How are model results viewed upon regarding: validity, use, and as a decision base?

RQ3. How was the response to this model compared to the previous Case A?

The case showed applicability using group model building for defining a manufacturing system and study its dynamics. The participants gained: learnings from discussions on a level that had not been attained before, and enlightenment on benefits from including soft parameters when considering change. The participants agreed that the model exhibited the studied system and that it will contribute to future implementation of solution. However, there were reservations on using the achieved results. In order to increase alignment a need of more efforts in experimentation and complementary modelling was identified. Altogether this case study showed larger engagement and commitment than previous study. It resulted in suggesting a *framework* for support *implementation* of a system dynamics project; in order to bridge the extensive need of pre-knowledge and practising skills that is required, and it should include group model building.

The method to obtain the results used:

- *System dynamics*: modelling and simulation using group model building, including; project design, interviews, preliminary model, model building sessions, workbooks, and experiments

- *Data collection*: primary interviews, information elicitation in group during modelling, and evaluation of participants' perceptions of the outcomes of the project

The group model building approach for system dynamics was used, including the client body into the process of modelling. Some more modelling experience had been attained since previous cases and the book of (Sterman 2000) provided better support than previously used material. The Vennix (1996) book supported setting the project design of the group model building case.

Information to modelling came in a more stepwise character than in the previous study, however modelling was still iterative. In the initial contact a review on the problem was made in order to decide if it could be modelled

using system dynamics. A causal structure could be defined, using a kind of sector mapping (Richmond 1994) which was very aggregated but included feedback behaviour (this method is included in the *framework* in figure 17). Initial interviews were conducted with each participant in order to build a preliminary model. Between session 1 and 2 a workbook was put together and filled in by the participants in order to elicit much information in short time. The modelling sessions was mainly characterised by discussions about the attained results and how the model could better show the studied system. Model changes were performed in between modelling sessions. Each session started by reviewing the upgraded model bringing further discussions and refinement. In the fourth and final session some scenarios were shown and described.
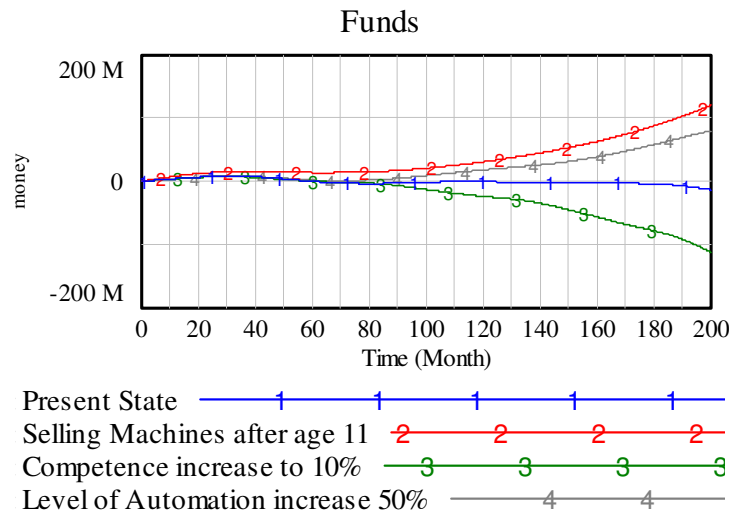
Funds

Figure 15   *Overall model behaviour from single policy changes*
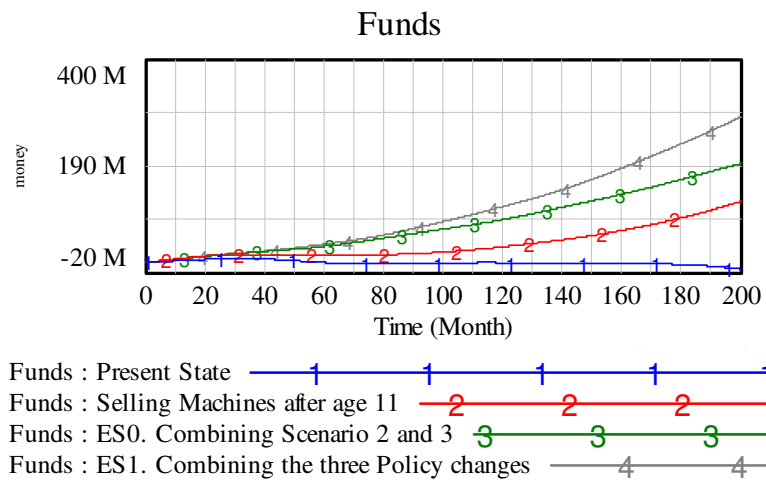
Funds

Figure 16   *Overall model behaviour comparing single and multiple policy changes*

The graphs in figure 15 and 16 show the results of scenarios in the parameter *Funds*; the accumulated profit from the chosen strategy. It is not the value itself that should be considered but the development of behaviours. Figure 15 shows the development from three separate policy changes and an index for present state. Figure 16 also shows the present state index, but presents how the results in *Funds* benefit from combining the efforts in all policies of action from previous figure.

4.2 GAP ANALYSIS

The gap analysis motivates the contribution of this thesis', by pointing on the need of a support for applying system dynamics for manufacturing systems development. It is based on input from literature and industrial case studies. The research question involves two sides of a gap that need to be bridged. This gap has an effect on usage of system dynamics in manufacturing. Identifying the gap facilitates how criteria for a support could be constructed for increased use in the context of manufacturing industry.

The two sides of the gap:

- *Academic theory.* Descriptions of *implementing* system dynamics projects provided by literature. This side is represented by the frame of reference chapter of this thesis.

- *Industrial practice.* Requirements on practical usage in the context of a manufacturer. This side represents *implementing* system dynamics projects in manufacturing in order to achieve better informed decisions for change. Moreover, this is dependent on the theoretical development of *Academic theory*; describing guidelines for manufacturing systems development.

4.2.1 Review of the Identified Lack of Use

The review identifies a lack of use in a general perspective, but focuses specifically on manufacturing systems development, including:

- *Management*. Low use due to pedagogical flaws in the methodology (Warren 2005) and failure in approaching "the current thinking in organisations and how these methods can move to organisational needs" (Wolstenholme 1997)

- *Manufacturing*. Low use due to that "system dynamics lacks a modelling platform that is tailored to the application of system dynamics to manufacturing problems" (Lin et al 1998) and "that manufacturing system modelling does represent a missed opportunity for system dynamics modelling" (Baines and Harrison 1999)

The identified lack has a spectrum characterised by:

- Unavailability for new users (Richmond 1994; Richardson 1996)

- Difficulties with *implementing* a modelling project (Richmond 1994) and limited support for such endeavour (Forrester 1994; Vennix 1996; Rouwette et al 2002)

- The field has produced quality results for practical use, however, it lacks a similar theoretic counterpart for how to perform projects; "no widely accepted and fully developed organisational intervention model for the use of the system dynamics methodology in an organisational context is available in the literature" (Zock 2004, p 1).

- Failure results from implementing modelling results in organisations (Forrester 1994; Grössler 2007).

- The practice suffer from a wide diversity in using group modelling techniques (Rouwette et al 2002), from studying 107 cases that applied group model building (years 1981-1999).

The frame of reference chapter mentioned eight problem areas for survival of the field; neither of these problem areas pointed out *implementation* of a modelling project as a problem. However, these listed arguments above clearly show that the *implementation* of modelling projects has lacking support in literature, also experienced in case studies. Either the focus of Richardson's (1996) presentation is too general for including this problem area, or Richardson has extensive experience in this and therefore oversees it as a problem. However, it is a problem and the essence of the gap presented in this thesis accordingly. Then:

Why does this gap of usage exist in manufacturing management?

Partly, this is described by the previous section, but it may also be explained by that the core of the field's research has moved from Industrial Dynamics (Forrester 1961) to study more important phenomenon for mankind, such as:

- Urban Dynamics, 1969 (Forrester 2000)

- World Dynamics, 1971 (Forrester 2000)

- The Limits to Growth (Meadows et al. 1972)

- System Dynamics in K12 education (Forrester 1996)

- National Model of economic behaviour in the US (MIT SDEP 2009)

- Climate Change (Sterman 2008)

Or it may be that the core of the field produces studies on a generic level for theory building, in for example:

  o understanding generic dynamic patterns for modelling (Wolstenholme 2004),

  o understanding success in business processes (Repenning and Sterman 2001),

  o and decision making in complex systems (Forrester 1970; Sterman 1994; Senge and Sterman 1994; Sterman 2001)

However, neither the case these aspects are reinforced by the inherent difficulty of the methodology which may have a vital factor; the paradox of both simplicity and complexity. On building block level it is a methodology easy to understand; the base elements of system dynamics modelling are elementary. But when these elements are to formalise a whole it becomes complex and difficult, and can be doubtful to rely on, as shown in Case C. With these building elements one can develop any diverse models generating endless complexity. Hence, the difficult part in modelling is formalising model equations (how model entities are interconnected), there exists no key for judging the soundness of each thought, besides your own creativity and ability to perform the art of modelling (Sterman 2000, p 87 and 89).

The difficulty of model building brings a level of unavailability towards the methodology, and no book can provide such comprehensive coverage. Literature describing the methodology use: covering technical modelling aspects (Sterman 2000) and alternation between theory and examples (Maani and Cavana 2007; Morecroft 2007). However, it is still needed to approach the entire content of such books in order to use it, and despite that, one may still feel uncertain in one's professional abilities.

In summary, there is a long delay until the methodology can be fruitfully utilized; experienced in processing case studies in this research, and also pointed on by (Richmond 1994). This highlights improvement potentials: For applications in manufacturing industry it could be aided by providing guidelines, supporting management to use the methodology. It should facilitate bridging the methodology's inherent difficulties. Consequently, to improve the identified lack of use, criteria for a support methodology should include guidance on how to perform system dynamics projects.

4.2.2 Other Approaches to Improve System Dynamics

Other approaches to increase the use from system dynamics have combined it with other systemic methods. These combinations are mainly motivated for, by researchers, by that they produce a more comprehensive analysis than achieved from using only system dynamics. For example combinations with: *Cybernetics* (Flood and Jackson 1991; Haslett 2000; Schwaninger et al 2004); *Soft Systems Methodology* (Flood and Jackson 1991; Rodriguez-Ulloa and Paucar-Caceres 2005); *Critical Systems Heuristics* (Flood and Jackson 1991); and *Artificial Neural Network* (Ren et al 2005)

There are also different combinations applicable in manufacturing:

- Balanced scorecard and system dynamics (Wolstenholme 1998; Akkermans and Oorschot 2002; Akkermans and Oorschot 2005; Nielsen and Nielsen 2008). Balanced scorecard is a management tool commonly practiced at manufacturing companies, widening the traditional financial view (Olve et al 1997).

- Improving corporate performance measurements using system dynamics (Affeldt 1999; Kennerley and Neely 2002; Vaneman and Triantis 2003).

- Discrete event simulation and system dynamics (Rabelo et al 2003; Venkateswaran and Son 2005).

- Theory of Constrains Thinking Process using system dynamics for enhancing its results, through providing with dynamic response patterns, testing policies, and quantitative validation (Reid and Koljonen 1999).

Combining system dynamics with an already known method has a potential use for stakeholders. This is exemplified by Warren (2005), describing the

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essence of management tools: that "practitioners will use methods that are perceived to be reliable, that they understand, and offer significant benefit in relation to the effort needed for their application" (Warren 2005, p 332). However a combination may also increase the required knowledge level, for system dynamics already being unavailable according to previous section.

In summary, combining system dynamics with other systemic methods may increase usefulness. However, for manufacturing management this is identified indeed increasing the gap for *implementing* system dynamics projects, due to increased need of knowledge. For that reason this is outside delimitations and hence excluded from criteria for a support methodology.

4.2.3 Issues in *Operational Management* Applications

In *operational management* applications of system dynamics there is an aspect of the client body. In order to provide good results from modelling, it is valuable if not essential with connectivity on the level of the client. According to Wolstenholme (1997) *operational management* might have problems with the system dynamics type of modelling. These issues are:

1. *Abstract Parameters,* including high level of aggregation parameters, generally making it difficult for *operational management* to relate to their own businesses

2. *Soft Variables,* the mix of soft and hard variables in modelling bring the consequence of a culture gap to previously used methods which are oriented towards hard variables

3. *Detail Escalation,* the tendency that each part of an organisation sees themselves most important requiring attention in modelling projects in order to keep model detail/ boundary on a decent level

4. *Model Ownership,* the desire for ownership of the model for future improvements is not included in the modelling process

If any of these aspects fail, it reinforces a non-use, showing the importance of acknowledging these issues for operational management. Moreover, the case findings have experienced the issues and show:

1. Troubles in relating to aggregated behaviours for client

2. Difficulties to consider other variables than the traditional hard facts

3. Strong tendency of wanting to increase model detail and boundary during modelling in order to better mirror the system

4. Lack of *Model Ownership* showed in evaluation

These aspects must be confronted wisely, requiring proper guidance when modelling for manufacturing management. Bridging these issues potentially increases the use as well as being aware of them.

In summary, these issues for *operational management* are not explicitly confronted in descriptions of system dynamics projects, however experienced in case studies. Previous identified criteria, regarding guidance for how to perform system dynamics projects in manufacturing, should benefit from acknowledging these *operational management* issues. Further, using a format of stepwise sequences in the guidelines enables confronting these aspects wisely in a project.

4.2.4 Summary of the Gap Analysis

The practical experiences of the case study research support the reasoning in the gap analysis. The gap analysis is a summary trying to explain the factors behind these experiences, which all result in unavailability to system dynamics projects as a method to manufacturing systems development. To bridge the gap improvements have to regard both the academic and practical side of the gap. These can be summarized, according to the gap analysis, as:

- It is difficult to *implement* system dynamics projects, partly because of the unavailability of the methodology and the limited support for it.

- Low use of system dynamics in both management and manufacturing, it would improve by acknowledging: using a tailored support for manufacturing; and approaching current thinking in organisations.

- Other approaches to increase performance in manufacturing have focused combining system dynamics with: balanced scorecard, corporate improvement measures, discrete event simulation, and the

theory of constrains thinking process. This research identifies this to increase the required knowledge of the target group of users.

- The target group of users, *operational management,* has certain issues with system dynamics modelling and should be confronted in a support.

In total, these aspects result in criteria for a support methodology to meet. The gap analysis points the need of guidelines for implementing system dynamics projects in manufacturing and that these use a format of stepwise sequences, assuring that information is provided timely.

4.3 METHODOLOGY DEVELOPMENT

The identified gap and case studies have resulted in defining criteria for methodology development, in order to achieve successful use from a support in manufacturing. These are presented below and cover the essential aspects when to develop a *framework* for support *implementing* system dynamics projects for manufacturing systems development. Meeting the criteria enable bridging the gap between academic theory and industrial practice identified by this thesis.

The support methodology can be divided into two levels that represent:

1. *An overall framework of guidelines for manufacturing use*

2. *A detailed level of stepwise instructions of use*

Base criteria for item number one are that it must:

1a. *Guide the user in order to bridge the gap for using system dynamics in manufacturing*

1b. *Provide appropriate concepts in order to cover the steps required for implementing a system dynamics project for manufacturing systems development*

The developed *framework* (figure 17) is defined with criterion *1a* in mind, shortening the distance for the target group to get going with system dynamics. The specific use, problem solving in a manufacturing context, enables a design specifically for such purposes. Present supports in literature are incomplete for *implementing* a project in practice. Closest

contribution might be Akkermans (1995), providing in "Modelling with Managers" a general methodology for designing modelling projects. However, it encompasses several options for how, and fall short bridging the criterion for item *1a*.

Criterion *1b* is motivated to be attained by the content of the *framework*. Those concepts included in the *framework* were used in Case C and considered appropriate for using system dynamics in manufacturing. Case C also evaluated the participants' experiences from the project as a quality assurance of content and use.

Base criterion for item number two is that it must:

> 2a. *Ensure that each concept includes the information and guidelines needed in order to enable implementation, either describing or referring best practice and if applicable be in stepwise sequences.*

Criterion *2a* is fulfilled by supporting how to use the *framework* concepts. This is shown on a general level, in this thesis, by a sequence schedule of the *framework* in figure 18, section 4.3.3.

4.3.1 Describing the *Framework*

Figure 17 summarizes the *framework* complemented by a list with brief explanations of the concepts. Each explanation includes a motivation, how they increase commitment with *operational management* (Wolstenholme 1997).
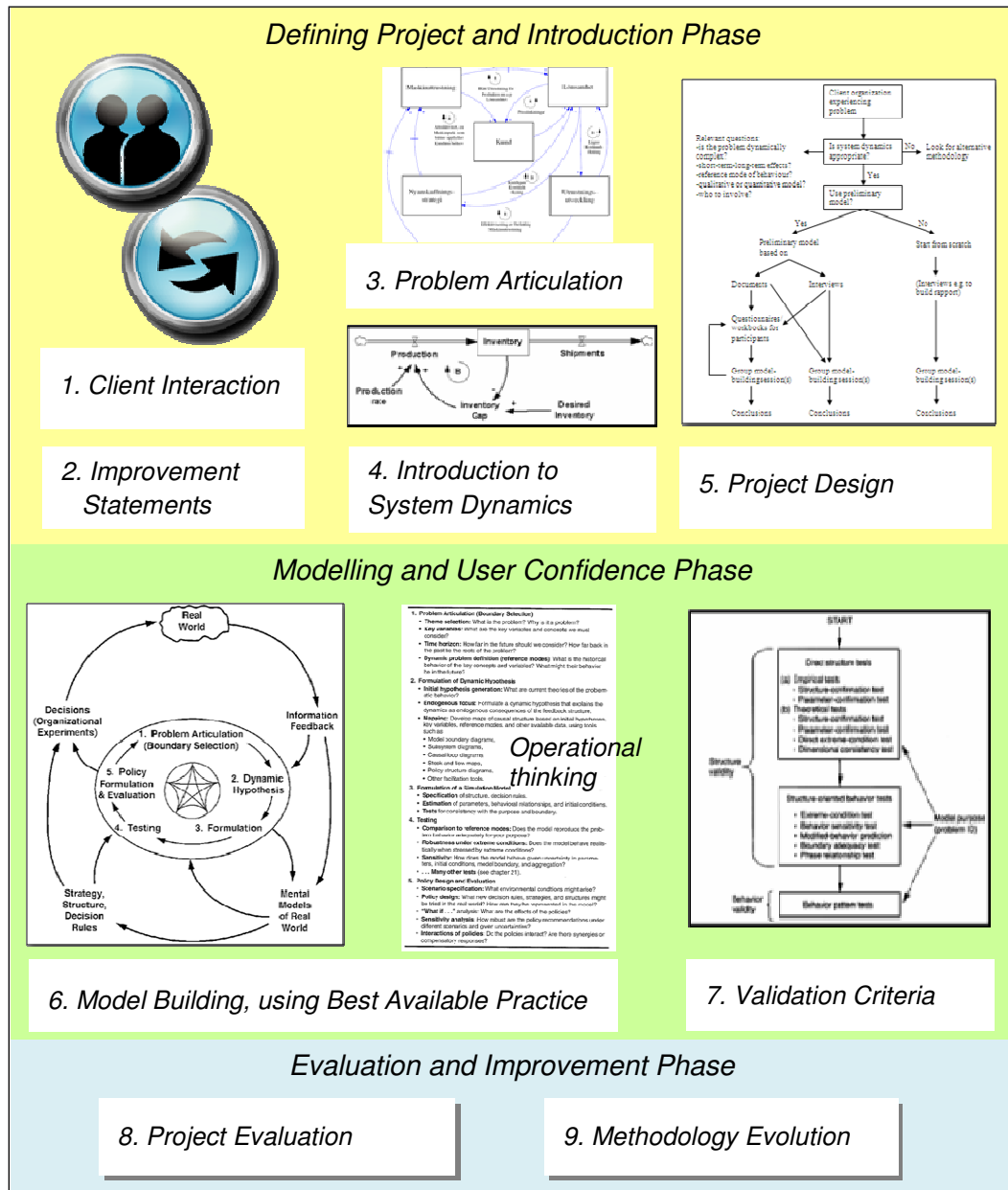
Figure 17   Summary of Framework

The concepts are:

1. *Client Interaction:* Actions in the project process which requires client interaction. For example, initially describing the generic change process in participants' mental model of the problem from modelling; this enables comparison of mental models prior to and subsequent to the project; this was missed in Case C. Moreover, it is necessary to prepare client on the problems *operational management* (Wolstenholme 1997) may have with system dynamics modelling. Bringing these problems up

is in order to acknowledge them in the start of modelling and during it, resulting in perhaps a better project and overcoming the issues.

2. *Improvement Statements:* In order to facilitate improvement results from modelling, setting a plan for development (*Improvement Statements*) is motivated and should be clearly addressed in a project. It make objectives with modelling more explicit and may bring possibilities to acknowledge *Abstract Parameters* thinking from start, preventing *Detail Escalation,* and providing *Model Ownership* when experiencing that the original statements can be approved. Case A and C lacked these statements, but it was due to the delimitations, focusing modelling and excluding implementing results in the real system.

3. *Problem Articulation:* The client's problem should be discussed in order to diagnose appropriateness of using system dynamics for solving it; was done in case study C. Sector mapping (Richmond 1994) is used for defining if system dynamics is suitable for the problem. It improves the ideas for how to formalise a real-system into a model which is a difficult aspect in modelling (Forrester 1994). Also, purpose is to identify if it is a feedback generated problem and if a reference mode of behaviour exists. The process of articulating the problem may impact *Model Ownership,* and should acknowledge it explicitly in order to facilitate for a successful project.

4. *Introduction to System Dynamics:* Includes describing basics; the thinking of feedbacks of cause and effect relations, and building blocks of stocks and flows etcetera for the modelling group in order to attain basic knowledge (Vennix 1996). Introduction benefits from approaching the problems for *operational management* (Wolstenholme 1997), preparing the group on those aspects for the modelling case, especially regarding *Abstract Parameters* and *Soft Variables*.

5. *Project Design:* Guidelines based on the work of Vennix (1996) brought up in the *Group Model Building* chapter. Group model building has been considered the proper method for manufacturing use in all cases, and Case C verifies it. The proper approach mainly for its capability of creating *Model Ownership*.

6. *Model Building:* Guidelines on the level of mainstream literature should be included in this concept. The technical modelling support mainly has

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to refer to best available practice. *Operational thinking* is advocated for since it has been used successfully in Case A and C. It is suitable to use in systems that include process flows and provides increased understanding for how to formalise a real-system into a model. The model building process has a large portion of client interaction and thus a substantial effect on success in how *Abstract Parameters* and *Soft Variables* are perceived. Model building is also the process where *Detail Escalation* appears and has to be confronted. Simulation experiments are encompassed for creating understanding of model behaviour. Case C showed importance of experimentation for achieving *Model Ownership*.

7. *Validation:* Those criteria valid for group model building should be part of the guidelines as well as reminders for when validation come about during the modelling process. For example, validation during modelling is when a specific model structure is agreed (Case C). Main purpose with validation is to create user confidence and *Model Ownership*.

8. *Project Evaluation:* Facilitates following up project results, based on project members' feedback. This accumulates knowledge for how to use the tool (Case C). It is performed before closing the project and may generate corrections of any misunderstandings. The timing of a follow up, in the final stage, may not affect the carried out project much, although it give chance to improve the *framework* for next time. Especially regarding bridging the four difficulties for *operational management*.

9. *Methodology Evolution:* The handbook of guidelines for using the *framework* should continuously be improved. After each project, checking the results increases the ability of the *framework* to support successful projects. Thus it may bridge the four difficulties for *operational management*.

4.3.2 Mapping the Relevance of the *Framework*

Table 1 concludes how the *framework* may facilitate using system dynamics for *operational management* in manufacturing, focusing on how the previously described concepts contribute to this. Table 1 highlights the relevance of these concepts to the 4 issues *operational management* have with system dynamics applications (Wolstenholme 1997). In previous text

the 9 concepts were mapped out towards each of the 4 issues, and are summarized by table 1. Explicitly showing how these concepts potentially support any of the 4 issues, marked by an "X".

Table 1   Summary of relevance for each concept

Issues for *Operational Management* with System dynamics applications	*1. Client Interaction*	*2. Improvement Statements*	*3. Problem Articulation*	*4. Introduction to System Dynamics*	*5. Project Design*	*6. Model Building*	*7. Validation*	*8. Project Evaluation*	*9.Methodology Evolution*
1. *Abstract Parameters*	X	X		X		X		X	X
2. *Soft Variables*	X			X		X		X	X
3. *Detail Escalation*	X	X				X		X	X
4. *Model Ownership*	X	X	X		X	X	X	X	X

4.3.3 Using the *Framework*

The methodology development chapter in this thesis provides mainly the motivation of the framework's construct; however, it can be further elaborated by the ideas for how to use it. The main idea with the *framework* is to support *implementing* system dynamics projects in manufacturing; hence it will provide the user in this context with a handbook for how to *implement* such projects. The *framework* will, firstly save time for the user: time for finding applicable information to get going; time it takes to prepare a project; support on setting the expectations on project; considerations

necessary to make before, during, and after modelling; and secondly provide the main thread through its support to a project's progress. These are valuable gains concluded by the *framework*, otherwise implicit in current available descriptions of how to *implement* system dynamics projects.

The handbook for how to use the *framework* should contain project guidelines and invoke external sources of support in order to complete it when necessary. The handbook, termed MSD Handbook (Manufacturing Systems Development), should concentrate following the sequence shown by figure 18, which span over all concepts previously described. The external supports defined necessary are: Sterman (2000), providing state of the art technical modelling aspects; and a simulation software enabling modelling and simulation. However, the MSD Handbook will use material from other sources as well but these can be included in its description, which is not due for the external supports.

In summary, how to use the *framework* should be provided in a handbook format. The purpose with the MSD Handbook (Manufacturing Systems Development) is to guide the user: saving time and support structuring a project, concluding necessary information in correct sequence. The project sequence is shown by figure 18 which includes all previously described concepts, required resources and their interaction, and when to use external supports or internal guidelines in the MSD Handbook.

Further description of figure 18: mainly the figure is self explaining. It sheds light on the sequencing of a project based on the *framework* contents. Resources in a system dynamics project are: Simulation Expert, Client Project Manager owning the problem, Client Model Group interested in solving the problem, and Simulation Team. How these resources are involved during a project is shown in each sequence, and for the complete "Implementing Project" box this is shown once for all three sequences in its right upper corner. Besides what is shown, closing project is made in accordance with the client project manager.

Initial Contact

Client Interaction

Project Manager
• Describing Problem

Simulation Expert
• Describing a System Dynamics Project

Defining Project

Improvement Statements

Project Requirement Specification

Project Manager
• Requirements

Simulation Expert
• Applicability using System Dynamics

Problem Articulation

Project Manager & Model Group
• Information Eliciting

Simulation Expert
• Sector Mapping

Final Decision

Is system dynamics suitable?

No → Describe Why, wrong method /or Rework, delimit boundary

Yes

Project Design

Agree on the design

Project Manager
• Requirements on Implementation

Simulation Expert
• Guidelines in MSD Handbook

Implementing Project
• Introduction to how the Project is set
• Introduction to System Dynamics

Group Model Building

Project Manager & Model Group

Simulation Expert & Team

Modelling
• Best Available Practice, MSD Handbook and external support using Sterman (2000)
• Validation (Direct structure tests)

↑ **Refinement**

Simulation
• Experimentation
• Validation (Structure-oriented behaviour tests)

↑ **Refinement**

Project Evaluation
• Did project add value?
• Redo? In order to increase results or user confidence
• (Set Improvement Plan...)

Close Project, Reporting to Client   **Simulation Team**

Methodology Evolution, Improving the MSD Handbook   **Simulation Team**
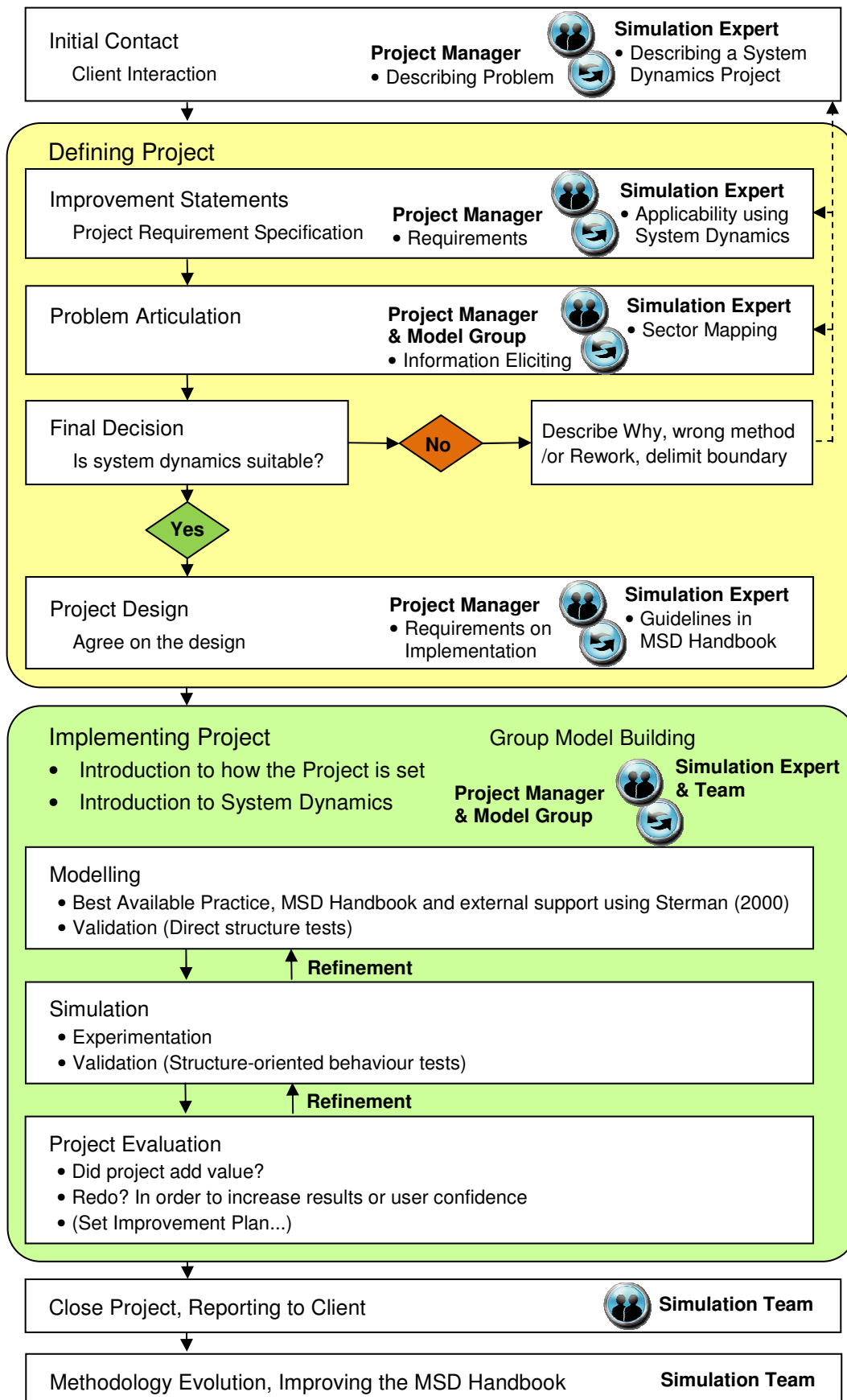
Figure 18   Sequence schedule of using the Framework, including actors

4.4 MAIN CONTRIBUTIONS

Case Studies

The research, of explorative interpretive character, in case studies has showed applicability of system dynamics for manufacturing systems development. However, poor support for *implementing* system dynamics projects has been experienced. Group model building is identified as a fruitful procedure for modelling as a mean to increase commitment for future solutions.

Gap Analysis

The findings from literature and cases have identified the situation of low use of system dynamics in management and manufacturing, unavailability for new users, and difficulties with *implementing* system dynamics projects and the results from them. The analysis also brings up a number of issues for *operational management* with system dynamics modelling. These issues were clearly confronted in Case C and may be key aspects to acknowledge for a support tool. The gap analysis shows the need of a support for *implementing* system dynamics projects in manufacturing in order to bridge the gap in the research question. Further it suggests criteria for the development of a support tool to acknowledge.

Methodology Development

A *framework* that support using system dynamics projects for manufacturing systems development is presented. It is the result of case study and literature findings and its construct is motivated for in order to increase use of system dynamics in a manufacturing context. It is based on criteria that define the level of support that is needed in order to bridge the gap between theory and practice. The relevance of the *framework* for *operational management* issues with system dynamics applications is also shown. The chapter closes with showing how the *framework* saves time for the user and structures a simulation project.

5 SUMMARY AND CONCLUSION

5.1 DISCUSSION

Problems are the result of past actions and are either eliminated by accurate measures or restrained by temporary solutions. Reality is a continuous flow of problems demanding attention from *operational management*; problems in which cause is separated from effect and effectively confuse system actors. A successful approach to such problem solving would be an asset in order to come ahead in the competition. System dynamics is a methodology that uses the language of systems, previously brought up in this thesis: it uses the "universal structure of real social and physical systems". However it is also a methodology that suffers from unavailability and the modelling procedure is much based on art and practising skills; a better support is needed. Most likely manufacturing businesses will continue to suffer under the continuous flow of problems. Introducing system dynamics for problem solving in this area could bring a tool for dealing with these issues. In this context the thesis is *novel* suggesting a *framework* to support applying system dynamics for manufacturing systems development. And can provide a valuable step towards more effective use of this methodology in manufacturing.

5.1.1 Correspondence to Objectives

The research objective is to *increase an organisation's ability to find key leverage points in an industry problem situation by using system dynamics.* This objective is supported by this thesis in accordance with:

- *Increase organisational problem solving ability:* Achieving mutual understanding of feedback behaviours in real-systems could signify the *ability to find key leverage points in an industry problem situation.* Providing a tool for facilitating understanding problems in manufacturing, together with corporate stakeholders, through

experimentation on change for better informed decision making for operative improvements are then considered positive for satisfying the first part of the objective. Literature and case studies verify that system dynamics, and especially using group model building, have the ability to provide such tool in manufacturing. This thesis presents a number of criteria for such a tool to meet. These criteria resulted in the presented *framework* which facilitates using system dynamics in manufacturing by explicitly framing suitable project guidelines.

- *By using system dynamics:* The second part of the objective focuses the utility of *implementing* system dynamics projects for manufacturing systems development. Reviewing the available descriptions of system dynamics projects indicates on improvement potentials. For that reason this thesis presents a *framework* concluding applicable project guidelines for manufacturing systems development. The *framework* improves the utility of such projects regarding: time for finding applicable information to get going; time it takes to prepare a project; support on setting the expectations on project; considerations necessary to make before, during, and after modelling. On these bases this thesis improves the utility of system dynamics in manufacturing.

The research objective is clearly supported by this thesis. The objective is also considered to be of relevance for the research project; it can be verified by that: If system dynamics was used effectively in the process of eliminating problems in manufacturing systems, it brings an *increased organisational ability to find key leverage points*. This thesis states that: the support for *implementing* a system dynamics project is the limitation; brought up in literature as an art and science of performing the methodology relying on practising skills. However, a more specific support could improve the science part and thus reduce the present limitation of use.

After considering how this thesis' results correspond to its objective, we go on to discuss the research question of this thesis:

> *Q1: What are the key enablers for bridging the identified gap between academic theory and industrial practice, of how to implement a system dynamics project for manufacturing systems development?*

Q1 must be considered in line with the objective and highly relevant as a foundation for further research. Although an alternative question to Q1 could have been used; focusing on examine applicability and utility of system dynamics for manufacturing systems development. However, this has to be opposed as a legible method at this stage. It would be difficult to generate sound empirics, since the lacking available support make system dynamics so dependent on art and skills. This motivates exploring the enablers for bridging the identified gap first, and not until after that better controlled studies for examining applicability and utility can be performed.

The answer to the research question is represented by the developed *framework*, presented in the *Findings chapter.* The *framework* is comprised of guidelines for bridging the key enablers for support using system dynamics projects for manufacturing systems development. Thus, this thesis sufficiently answers the question Q1 from a scientific point of view. Even if further research is necessary in order to answer the question on a practically verified level; see *Further Research chapter* below.

5.1.2 Validation

The factors for validating qualitative research from Olesen (1992) have been used in order to test the results. Each factor is followed by a discussion in order to show how the achieved results meet the validation criteria:

Internal logic: The results are based on known and accepted theories, and there is a logical sequence connecting the research problems, hypothesis, and the results. The results must be considered to meet the criteria of the internal logic factor. The research results are based on: accepted theories, a structured explorative research procedure, and literature and case study findings. The findings have resulted in a *framework* which uses elements identified during research to improve the *implementation* of system dynamics projects for manufacturing systems development. The results are based on an internal logic throughout the research project represented by this thesis.

Truth: The theoretical and practical results can be used to explain "real" phenomena. The research has been carried out at a manufacturing company in an environment that requires practical use which assures the level of truth. Case studies have been studying real-world problem phenomena using action research for testing and evaluation. In this sense practical

results have been truthful to explain real phenomena. The developed *framework* concludes the results and is based on published literature and case studies. In conclusion this must be considered to satisfy the truth factor on this level. It can be argued that few samples have been used which make it difficult to claim generality. However, on this level of qualitative research generality has to confirm to analytic generalisations of few samples.

Acceptance: Other researchers accept theories used in the research, and professionals are willing to use tools based on the theories. The system dynamics field is a large community which has published in numerous journals and also has a journal on its own. And it is a widely used methodology, although being represented at a low level at Swedish Universities and industries. Group model building is one type of system dynamics widely used, although as previously pointed out also lacking a consistent theoretical framework. There is also criticism that system dynamics have not reached the top-fifty-list of applied management tools. However, in total this factor much be considered attained.

Applicability: Application of the results increases the probability of successful problem solving. It does not necessarily lead to success every time, but over a period of time it will give better results than if not applied. The developed *framework* is not practically verified in this research project. It is verified through the learnings from case studies, indicating on aspects worth to consider for manufacturing systems development and therefore included in the *framework*. It can be considered that using the *framework*, even if it is not yet completely developed, surely increases the probability of successful projects compared to not using it. In other words, if a *framework* would have existed prior to this research project, it would have facilitated applying system dynamics in manufacturing saving lot of time. This supports the validation of applicability.

Novelty value: New solutions are presented, or new ways of looking at a particular problem introduced. The practical approach of *implementing* system dynamics projects presented by this thesis has a *novelty* value. Previous supports are provided in terms of study books and focus on isolated parts leaving the puzzle dependent on the practicing skills of the modeller. Bringing these parts together, dedicated for manufacturing systems development, may thus add value and be a support for applying

system dynamics in that area. Definitely it saves time for new users when it comes to, orientate in and get to know about the proper tools and procedures to select from. Further the work presented in this thesis brings the opportunity to involve corporate stakeholders which render possible for management to actively manage manufacturing through the making of policies.

5.2 CONCLUSION

The objective with this licentiate thesis is to answer one research question as a response to the identified problem of lacking guidelines for using system dynamics projects in manufacturing. The research question is:

> *Q1: What are the key enablers for bridging the identified gap between academic theory and industrial practice, of how to implement a system dynamics project in the context of Swedish manufacturing businesses?*

The discussion shows that the objective is met on a satisfactory level in this thesis. The following conclusions can be drawn from the results:

- The support for how to *implement* system dynamics projects is presently provided on an unsatisfying and general level

- A selection of concepts supporting system dynamics projects for manufacturing systems development have crystallised during the research process

These two conclusions have resulted in a *framework*; which in total provides those key enablers for bridging the existing gap. The *framework* is based on a set of important criteria that have been identified vital for bridging the gap. These criteria are:

- *Guide the user in order to bridge the gap for using system dynamics in manufacturing*

- *Provide appropriate concepts in order to cover the steps required for implementing a system dynamics project for manufacturing systems development*
    - *Ensure that each concept includes the information and guidelines needed in order to enable implementation, either describing or referring best practice and if applicable be in stepwise sequences.*

For greater detail of how the developed *framework* acknowledges these aspects, please look into *Findings chapter*.

5.3 FURTHER RESEARCH

Further work in order to attain the research objective presented in chapter 2 more completely suggests following procedure:

1. Put the suggested solution from this thesis into practice, by:

    a) Development of the *framework* into a more defined support for manufacturing systems development; a process of testing in case studies in order to improve the support and verify its content.

2. Verify how well the research objective is supported, by:

    a) Verify the usefulness of the developed support for system dynamics projects; a process requiring a number of cases also performed by undergraduate students.

    b) Evaluate the summarized empirics on how well the objective of achieving *increased organisational problem solving ability* is met by the developed support, the result will strongly depend on its effectiveness.

During these processes it is important to concurrently evaluate if it is worth to *implement* system dynamics projects as to required input and achieved output using the *framework*. If the output is considered too low it is necessary to approach that and further focus on refinement in order to improve the input output relation.

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