1 Introduction

This introductory chapter gives the reader an orientation for this thesis. Section 1.1 describes the background to Empirical Modelling (EM). Section 1.2 describes the motivations and aims that underlie the research reported in this thesis. Section 1.3 outlines the contents of the thesis. Section 1.4 discusses the principal contributions of the research described in this thesis to EM.

1.1 Background

The Empirical Modelling Project is an ongoing research programme, based in the Computer Science Department at the University of Warwick. The project was initiated by Dr. Meurig Beynon in 1981, and has subsequently received sponsorship from British Telecom, IBM, Matra Datavision and the BBC, and conducted collaborative research in association with universities in Europe, Japan, Russia and the US. The published output of the project includes over 100 publications in the form of international conference and journal papers, research reports and doctoral theses. In addition, several software tools have been developed, together with several hundred models generated through postgraduate and undergraduate project work to study the potential practical applications of EM.

A major theme of the project is studying principles and building tools for constructing 'construals' of phenomena, typically as special computer-based models. The emphasis is not on making a product, but on model-building activities that assist the personal cognitive process of understanding phenomena and the interpersonal sharing of understanding. The choice of the epithet 'empirical' reflects the fact that the modelling activities are rooted in observation, interaction and experiment, and in this respect are distinguished from perspectives that are associated with formal methods and traditional mathematical models.

A radical distinction between EM and many other approaches to computer-based

modelling is its explicit emphasis upon modelling state as directly experienced rather than behaviours as circumscribed. Key modelling activities are associated with the identification of agents, dependencies and observables that arguably resemble our commonsense way of understanding phenomena as experienced in everyday life. Accordingly, the modelling activities are situated and subjective in nature, so that – unlike most conventional methods – EM presumes no fixed steps in the model-building process. Instead, modelling activities are guided by heuristic observation, interaction and experiment supported by the construction of an interactive computer-based model which metaphorically represents the modeller's construal that is always open to evolve in response to changes in the current situation and viewpoint.

EM research has found potential applications in many areas that include human-computer interaction, software development, computer-aided design, geometric modelling, behavioural modelling, concurrent engineering, educational technology, cognitive technology, artificial intelligence and business systems. In the context of these various applications, ideas about system development in general have been discussed, but only at the level of detail that is most relevant to the particular application area. This thesis seeks to consolidate and extend different ideas relating to system development that have been generated in previous research, and gathers them into a unified framework. It is the first thesis to focus on the EM approach to system development in the most general context.

1.2 Aims and motivations

The primary aim of this thesis is **to explore EM as a distinctive approach to system development**. The thesis is motivated by a large body of literature in philosophy, experimental science, cognitive science and computer science that stresses the importance of the experiential, experimental and informal nature of interaction between humans and the world that has become topical in relation to computer-based modelling in recent years. We briefly introduce some of the most influential ideas that motivate this thesis as follows:

- In his essays on radical empiricism [Jam96], first published about a century ago, William James sets out a philosophical position that accounts for knowledge in experiential terms. EM emphasises techniques for the acquisition and representation of knowledge that are experiential in nature,

and that are associated with the process of model-building in system development.

- In [Goo00], Gooding describes the importance of using concrete artefacts to embody and assist the cognitive process of understanding phenomena in experimental science. EM supports the construction of computer-based artefacts for system development that have qualities similar to those of Gooding's artefacts.
- In [Tru00], Truex et al. describe the notion of 'amethodical' information system development, where the development process is not formalised. EM aims to support situated modelling for system development, but prescribes no general method for system development.
- In [Cro96], Crowe et al. advocate a constructivist approach to system development that emphasises "the mental and social nature of the construction of forms of information". EM aims to support cognitive processes in system development at both personal and interpersonal levels.
- In [Bro95], Brooks contends that *conceptual integrity* is the most important consideration in a system design. EM aims to provide principles and tools that help to maintain conceptual integrity in system development.
- In [Weg97], Wegner argues that interaction is more powerful than algorithms. EM encourages the interactive construction of models that can support human problem solving aspects of system development.
- In [Wes97], West advocates that *hermeneutic* computer science (which focuses on aspects of the informal natural world) as a complement to traditional formalist computer science (which focuses on aspects of formal deterministic worlds) in order to build complex systems. EM provides principles and tools that can be regarded as advances in hermeneutic computer science.

A key feature of EM (to be discussed in detail in chapter 2) is the construction of computer-based models that serve to embody the modeller's construal of phenomena in respect of agency, the observables that mediate this agency and the dependencies that link these observables. In developing a system, there are two complementary ingredients – the construction and configuration of system components, or of prototype models for these components, and the emergence in the minds of the developers of a system construal that reflects their commonsense explanations and expectations concerning how these components interact. These two ingredients of 'system construction' and 'system conception' which together make up 'system realisation' are both represented in EM. Model-building activity in EM is broader than

system realisation in that it embraces the construction of experimental models whose purpose is to inform the modeller about the salient properties of the environment in which the system is to be established. Moreover, an EM model to represent a system component embodies the relevant observables and dependencies using a style of representation (namely a 'definitive script') that typically supports interactions beyond the scope of the actual component.

In view of the above observations, the EM approach to system development is not easy to compare directly with traditional system development methods. For this reason, in this thesis, the EM approach to system development will be discussed in association with two perspectives on systems that are identified in the thesis title, namely *before systems* and *beyond systems*. When adopting a 'before systems' perspective, we are considering the extensive preliminary activities that help to inform the system conception, and in particular with the way in which a system design with conceptual integrity may emerge from this activity. When adopting a 'beyond systems' perspective, we are concerned with exploiting the power of EM to develop computer-based models that can fulfill the functions of a system without the circumscription characteristic of traditional systems. This enables us to develop embryonic system-like configurations of components that can be customised and optimised to serve as a conventional system at the point of use. In this style of application of EM, which has been extensively illustrated in previous research (see e.g. [Run02]), the sharp distinction between a developer and a user is no longer appropriate. This theme is particularly relevant to modern ubiquitous computing environments, where modes of use are so dynamic that they cannot be captured in advance.

The primary aim can be subdivided into three more specific aims. We list these aims together with their motivations as follows.

- **Aim 1: to unify EM ideas for system development within a coherent framework.** This thesis seeks to unify ideas represented in specific applications of EM and abstract more general principles from them. The motivation behind this aim is that, over the past 20 years or so, the EM project enjoyed a steady growth of ideas and concepts about system development that are scattered in the EM literature. However, so far there has been no explicit attempt to give a coherent account of EM for system development in the most general context. This thesis aims to consolidate on and amplify EM principles for system development that can be applied to any application domain.

- **Aim 2: to expose the potentially comprehensive nature of EM as an approach to system development.** An approach to system development that is comprehensive in nature must be able to deal with its wide variety of applications and address its human aspects. With this in mind, this thesis studies the EM approach to system development in detail from several different angles. The picture of EM for system development that emerges depicts system development as a complex cognitive and social human activity that admits no formal prescription.

- **Aim 3: to evaluate the existing EM tools and explore new ways to build better tools.** This thesis aims to evaluate the existing EM tools in terms of how well they support the concepts of EM. Based on the issues identified from this evaluation, we aim to explore new ways to build better EM tools. The motivation behind this aim is that the development of EM tools has not kept up with the rapid development in research into EM concepts and principles. As a consequence, the existing tools cannot fully realise some important EM concepts.

1.3 Thesis outline

This thesis consists of nine chapters, structured as follows. Firstly, we give an overview of EM concepts (chapter 2). Secondly, we discuss this EM approach to system development in relation to traditional system development research. This includes a macro 'bird's-eye' view that gives an overall description of the EM perspective on system development (chapter 3), and a micro view that discusses the human problem solving that system development using EM entails (chapter 4). Thirdly, we discuss the themes of 'before' and 'beyond' systems. This includes the discussion of conceptual integrity as the essence of the system concept (chapter 5), and the discussion of ubiquitous computing with reference to the new perception of a 'system' that can be supported by EM (chapter 6). Finally, we turn to the investigation of EM tools to support the activities that underlie EM. This includes evaluations and prospects for EM tools (chapter 7), and description of a new visual EM tool (chapter 8). These two chapters describe tools for building systems and contribute to filling the gap between EM principles and implementations. The thesis concludes with a summary of ideas developed during the preparation of the thesis and proposes

relevant further research directions (chapter 9). Figure 1.1 depicts an overview of the contents in each chapter.

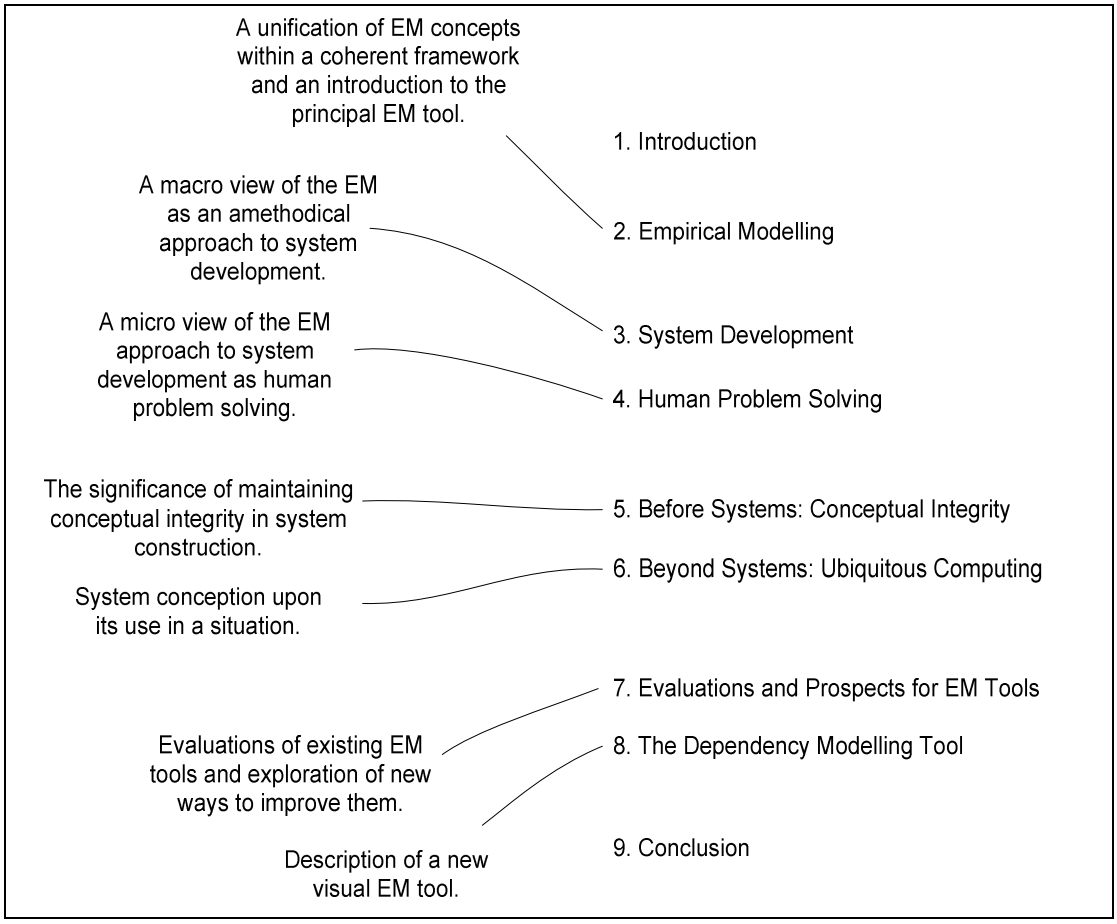

Figure 1.1: A summary of the thesis content

The contents of each chapter can be summarised in more detail as follows:

- **Chapter 2: Empirical Modelling.** In this chapter, we shall give the reader an overview of EM principles and tools. The content of this chapter is organised in such a way that it gradually moves from abstract concepts to concrete implementations. It starts with a discussion of the underlying philosophy of EM. Then, it introduces the modelling framework that is based on the underlying philosophy. Finally, we explain how the framework is realised in practice. This chapter should not be regarded solely as a literature review. Since the concepts of EM have themselves been evolving over the past 20 years or so, this chapter can be regarded as a consolidation of EM concepts introduced previously. In particular, we gather EM concepts into a unified and coherent framework (the Definitive Modelling Framework) that can be characterised by particular concepts of representation, and types of modelling activity associated with a

distinctive interactive style of model building.

- **Chapter 3: System Development.** Promising applications for EM concepts have been identified in many research areas. The wide range of potential applications of EM gives some empirical evidence for the generality of EM concepts in respect of system development. However, there has been no attempt so far to account for this generality explicitly. In this chapter, we shall explore the generality of EM concepts and argue that the philosophical foundation of EM is domain-independent. The structure of this chapter is as follows. Firstly, it reviews some of the research strands in the literature on system development. These strands will be contrasted with the EM perspective on system development discussed in later sections. In addition, we shall specify the principal aims for the application of EM to system development. Secondly, our discussion will focus on thinking about intrinsic properties of systems and their relationship to an EM perspective on system development. Thirdly, we focus on thinking about system development activities and discuss how EM takes these activities into account. Finally, we conduct a case study of modelling a dishwasher system in both EM and another common modelling approach, object-oriented modelling using UML. Our aim is to explore the differences between these two styles of system modelling. This chapter concludes with a review of possible ways in which the aims of applying EM to system development set out earlier in the chapter can be achieved.

- **Chapter 4: Human Problem Solving.** This chapter focuses on the application of EM to support the human problem solving that is arguably the most important activity in system development. Firstly, we discuss the importance of developing principles and techniques for using the computer to support human problem solving. Secondly, we explore the relationship between problem solving and programming, with reference to some relevant research from the fields of general problem solving and psychology of programming. We shall argue that conventional programming paradigms cannot give comprehensive support for problem solving. Thirdly, we propose EM as a better approach for supporting problem solving. Finally, we present a case study based on a real life timetabling problem.

- **Chapter 5: Before Systems: Conceptual Integrity.** In his famous book, The Mythical Man-Month [Bro95], Brooks contends that “conceptual integrity is the most important consideration in system design”. This chapter endorses and

elaborates this idea, and contends that obtaining conceptual integrity is essential before a coherent system concept can be formed. We believe that conceptual integrity emerges from activities that are prior to system identification or formalisation. Alongside this discussion, we shall explain how the EM approach to system development helps to address the issues of maintaining conceptual integrity. We start with a discussion of the meaning of conceptual integrity. The discussion leads to the identification of issues that are important to the maintenance of conceptual integrity. We shall discuss how EM can help to address them. At the end of the chapter, we shall also compare EM with other technologies that can be regarded as approaches to maintain conceptual integrity.

- **Chapter 6: Beyond Systems: Ubiquitous Computing.** In this chapter, we discuss how EM principles can potentially be applied to everyday practical computing as it may be in the future, where the system conception is only established upon its use in a situation. Following Weiser [Wei91] we adopt the term ‘Ubiquitous Computing’ or in short ‘ubicomp’ to refer to an era where people will use a variety of computer-based devices to support everyday activities. We firstly identify a variety of research related to ubicomp. We discuss and summarise their shared visions. We argue that these visions are hindered by the lack of a conceptual framework to encapsulate the complexity and new requirements of ubicomp. In particular, little research has so far been conducted to develop a conceptual framework that explicitly supports both the design and the use of ubicomp devices. We argue that having a coherent conceptual framework is very significant for maintaining the conceptual integrity of ubicomp systems, and that this will be fundamental to the success of ubicomp. We introduce a new conceptual framework namely SICOD (Soft Interfaces for the Control of Devices) based on EM principles and tools and illustrate this with examples. We shall discuss challenges involved in realising the framework. Finally, we shall describe some related research and make comparisons between them and our proposed framework.

- **Chapter 7: Evaluations and Prospects for EM tools.** In this chapter, we shall explore different techniques and tools that can be used to support the activities of EM. Our objectives are to evaluate existing and possible future implementations and to discuss the prospects for future development of EM tools. The chapter starts with a discussion of the essential characteristics of an ideal EM tool. This is to set the context for the evaluations described in later

sections. The chapter then considers three existing technologies, Java, Excel and Forms/3, as possible EM tool implementations. Following this, we evaluate the principal EM tool: TkEden. Finally, we introduce two new EM tools (WING and EME) and highlight some of their prospective advantages based on researches described in previous sections.

- **Chapter 8: The Dependency Modelling Tool.** In this chapter, we shall describe a new EM tool, the Dependency Modelling Tool (DMT). The motivation for developing the DMT is similar to that of developing WING and EME – they aim to enhance the users' experience in the process of EM. However, the emphasis in DMT is on the ways to visualise various structures that commonly exist in EM models. We start out by identifying these structures and describe some tools developed by others in relation to visualising structures that are similar to the ones that exist in EM models. The development of DMT is partly inspired by some features of these tools. We then introduce DMT's user interface with a simple example. Followed by this, we describe how DMT helps to address two major concerns associated with an EM model: model comprehension and reuse. The final section highlights various issues relating to further research and development of the DMT.

- **Chapter 9: Conclusion.** This final chapter gives a summary of the research discussed in this thesis and discusses potential research that might be conducted in the future in relation to the work in this thesis.

1.4 Research contributions

This thesis explores EM as a distinctive approach to system development. The author's principal contribution has been to supply a comprehensive account of the essential ingredients of the EM approach to system development in the most general context. This thesis consolidates previous EM researches within a coherent and unified framework – the Definitive Modelling Framework (DMF). The DMF provides support for all the essential characteristics of EM. These include: the representation of our commonsense 'construals' of phenomena; situated model building activities that lead to the development and sharing of these construals; and an emphasis on open-ended experimental interaction.

The work in this thesis develops general principles for using EM to address the issues of system development with reference to two research strands, associated with ‘thinking about systems’ and ‘thinking about system development activities’. Where thinking about systems is concerned, the thesis identifies three intrinsic properties of systems (complexity, predictability and unity) and discussed each in association with EM principles. Where system development activities are concerned, the thesis identifies three important aspects of such activities that can be classified as cognitive, collaborative and methodological, and discusses how EM can address issues associated with all three aspects.

The thesis also contributes to linking EM to ideas of heuristic human problem solving that are arguably the most important aspect of system development. By giving illustrative examples, the thesis has given evidence that EM principles and tools offer essential support for the modeller to solve problems in an experimental trial-and-error fashion.

This thesis also makes an important contribution to analysing and exploring the notion of conceptual integrity and explains how EM can address the issue of obtaining conceptual integrity which is arguably the most important consideration in system conception.

In addition, this thesis contains the first discussion of EM in relation to ubiquitous computing, where the functional requirements of systems are so dynamic that they cannot be prescribed in advance. The thesis introduces the concept of a ‘soft interface’ as a means to support the configuration of ubiquitous devices as agents that constitutes end-user programming in this setting. A soft interface is essentially a simple EM model that facilitates the management and customisation of agents whose reliable behaviour has been identified.

Apart from these theoretical contributions, this thesis makes significant contributions to research on EM tools. In particular, it includes an evaluation of the principal EM tool (TkEden), and explores the possibilities for implementing EM tools using various existing technologies. The author has also developed three prototype tools to explore new possibilities for better tool implementations which are more suitable for novice users: the Windowing and Graphics tool (WING) – originally developed as an undergraduate project [Won98] and subsequently enhanced by the author in the preparation of this thesis, the Empirical Modelling Environment (EME) and the Dependency Modelling Tool (DMT).

During the preparation of this thesis, the author has contributed to three refereed publications [Bey00b, Bey01a, Bey01b]. The EM models built by the author as case studies in this thesis include: the Dishwasher model (chapter 3), the interface for the Temposcope (chapter 4), the Crossnumber model (chapter 4), the drink stock control model (chapter 6), the central heating control model (chapter 6), the Business Deal models (developed for the tool evaluations in chapter 7 by using TkEden, Excel, Java and Forms/3) and the ATM model (chapter 8).