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Agent-Based Simulation New Product Development Processes

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Abstract: New Product Development Processes (NPDP) involve a series of functional teams who work in a complex information communication network. Agent-Based Simulation (ABS) comprises a set of autonomous agents that act and interact complying with simulation specifications within a simulation world. This paper analyzes key features of both new product development processes and agent-based simulation. A simulation mapping is introduced to highlight mirror relationships between key elements of new product development processes and key concepts that underpin agent-based simulation. We introduce a new product development process case study arising from a large UK-based manufacturing company, and an agent-based simulation model to represent the new product development process. Simulation results show that agent-based simulation is a promising method to study and explore complex socio-technical systems such as new product development processes.

Keywords: New Product Development Processes, Agent-Based Simulation, Modeling and Simulation, Simulation Mapping

1. INTRODUCTION

New product development processes (NPDP) are complex engineering systems that are used to design, develop, and deliver new products and services to market. The new product development process comprises a series of functional work teams that work on their design commissions within a complicated information communication network [1, 2]. Complex design systems, such as new product development processes, are associated with not only technical issues but also organizational aspects which significantly increase system complexity. Research and practice show that many challenges within such complex systems do not come from technical perspectives, but from social-related issues. For example, Farrell and Hooker argue that a typical characteristic of many design systems is that the design process is itself a wicked problem, associated with and caused by complexities of the design system [3].

This further increases the difficulty of studying new product development processes and their nature. Three challenges for researchers in this area are: 1) new product development processes are complex socio-technical systems (STS) that involve both technical issues and organizational concerns; 2) new product development processes take a long time (often years) to complete to full scale design and delivery to market; and 3) it would prohibitively expensive to operate a new product development process in the real-world and observe its operation in situ. In addition, socio-technical features of new product development processes and new product development performance indicators are emerging research fields.

Modeling and simulation techniques are being widely applied in complex societal and scientific systems. Two common process modeling and simulation methods applied in operational research are discrete-event simulation (DES) [2] and agent-based simulation (ABS) [4]. The application of modeling and simulation methods to understand performance of organizational systems is becoming a promising research approach [5, 6]. To some extent, modeling and simulation technology is being considered as the third science research methodology, in addition to the traditional deductive and inductive reasoning [6, 7].

The agent-based simulation (ABS) method has a number of advantages in investigating complex operational systems, such as new product development processes. Firstly, it takes less time to model and simulate such complex systems, and then observe their operation situations and performance. Secondly, it costs nothing to mimic a new product development process in a simulation model. And finally, it enables researchers to conduct series of simulation experiments with different inputs and observe the impact of these inputs on distinct outputs, in order to explore characteristics and performance impacting factors in new product development processes.

This paper introduces new product development processes and their key characteristics (Section 2), and modeling and simulation techniques (Section 3). an agent-based simulation mapping to new product development processes is presented in Section 4 and used in Section 5 to inform a simulation case study. Conclusions and future work are summarized in Section 6.

2. NEW PRODUCT DEVELOPMENT PROCESS

This section introduces new product development processes, different new product development process models, new product development performance indicators, and concludes with key characteristics of new product development processes a conceptual model that can be used to inform the design of agent-based simulation models of new product development processes.

The processes used to design and develop new products and then support them through their life-cycles are referred to in a number of ways: for example, product development process [8, 9, 10], new product development [11], new product process [12], new product introduction process [13], product service system [2], enterprise engineering system [14], product life-cycle [15], design iteration process [16], Stage-Gate system [17], product launch system, phased review process, and many others. In this research, the terminology of new product development process (NPDP) was used to refer to these kind of process and system.

2.1. Different New Product Development Process Models

New product development processes include a series of functional work teams, for example, preliminary design, detail design, manufacturing, distribution, after-sale service, and others [8]. Cooper established a Stage-Gate system that involves four stages (work teams): preliminary investigation, business case, development, and test & validate [12]. Functional work teams at each stage carry out specified design commissions and deliver work packages to the next stage to defined deadlines. Review processes occur at each gate where a decision is made on whether the product can proceed to the next stage, stops or requires rework in an earlier stage. Fig. 1 gives the skeleton of Stage-Gate system.

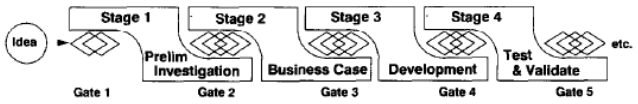

Fig. 1 Stage-gate system [12]

New product development processes involve complex technical and organizational considerations. In additional to technical design capacity, new product development processes are sensitive to socio-related impacting factors, e.g. organizational behavior, enterprise culture, employee education, policy, market and finance, geography, and others [18]. This increases complexity and so difficulty for information communication within such design and development systems.

New product development processes are typical complex engineering systems, which include a series of functional work teams and an extremely complex information communication network. Each work team requests information from other teams, and at the same time provides information in response to other team's requests. Therefore, macro-level performance of new product development processes is influenced and determined by the quality of micro-level information communication and decision makings between functional work teams.

2.2. New Product Development Process Performance Indicators

Traditional performance indicators for new product development processes are often referred to as the Iron Triangle: TCQ, i.e. Time, Cost and Quality. Companies try to increase product development system performance and efficiency in order to shorten product research and development (R&D) duration and time-to-market [19].New product development processes typically take in the order of months or years to develop a new product, with few products being developed in less than one year and many requiring three to five years, and some as long as ten years [8]. For this reason, time-related performance is a primary consideration from both business strategy and shareholders perspectives. To reduce time to market, it is essential to consider work teams' behaviors, information communication and decision-making in the sub-processes, in order to examine overall time-related performance of new product development processes.

2.3. New Product Development Process Features

As introduced above, new product development processes includes a series of functional work teams and a complex information communication network. Their key characteristics can be decomposed into the following:

- A series of functional work teams with specific design commissions;
- An information communication network that links each work team;
- Decisions made by each team influence other teams' and overall system performance;
- Macro-level performance is determined by micro-level work teams' behaviors and performance.

Fig. 2 illustrates these key features of new product development processes in the form of a conceptual model. Different nodes in the diagram represent work teams in new product development process, and two-way arrows represent information communication channels between all work teams. New product development process performance is determined by work teams' activities, behaviors, the quality of communications, and decisions made by individual work teams.

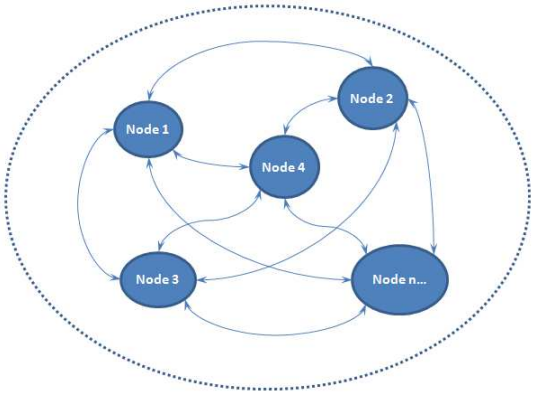

Fig. 2 New product development process conceptual model

3. AGENT-BASED SIMULATION

This section introduces modeling and simulation concepts and applications, two distinct modeling and simulation fields, and two popular modeling and simulation methods, i.e. discrete-event simulation (DES) and agent-based simulation (ABS). This section concludes with key characteristics of agent-based simulation.

3.1. Modeling and Simulation

Let us begin with two definitions of modeling and simulation. Modeling and simulation are defined as driving a model of a system with suitable inputs and observing the

correspondingly outputs [20]. Another definition takes the view that it is a process of designing a model of a real-world system (or a to-be system), that is used to conduct experiments for the purpose of either understanding the performance of the system and/or evaluating various management strategies and decision-making through simulation results [21, 22].

The purpose of modeling and simulation includes prediction, performance assessment, training, entertainment, education, proof and discovery [6]. The application of simulation techniques is widespread, spanning areas application domains such as computer systems, manufacturing processes, business organizations, government systems, ecology environment systems, social systems, and other complex systems [21, 22].

Modeling and simulation methods are widely applied to interdisciplinary research fields, for example, design process decision-making mechanisms [23, 24], integrated product development team management [25], new product introduction systems [26, 27, 28], and organizational management [5].

3.2. Two Distinct Modeling and Simulation Fields

Modeling and simulation techniques are broadly applied into two distinct areas: mechanism simulation and process simulation. Mechanism simulation relates to the simulation of physical mechanical systems, through which movement and velocity of mechanical components can be simulated and analyzed for whole machine optimization, e.g. kinematic simulation of 3D CAD models [29]. An example is shown in Fig. 3.

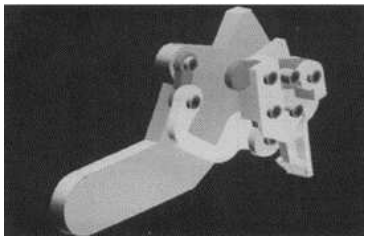

Fig. 3 Mechanism simulation [30]

On the other hand, process simulation relates to the simulation of process-based systems and their operational performance, including industrial production processes, business service processes [6], manufacturing systems [31], organizations [32], human systems [33], complex problem-solving process [34], and automotive assembly lines [35]. One example is shown in Fig. 4.

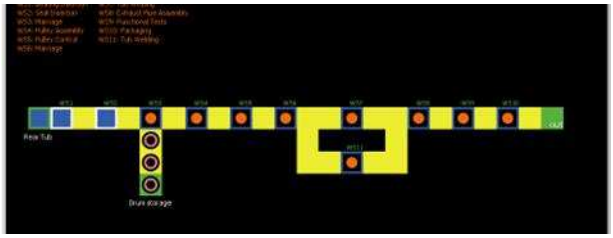

Fig. 4 Process simulation [31]

In this research, the terminology of simulation is exclusively used to represent process simulation.

3.3. Two Modeling and Simulation Methods

In addition to simulation methods such as Monte Carlo and mathematical simulations, two popular simulation methods applied in operational research communities are discrete-event simulation (DES) [2] and agent-based simulation (ABS) [4].

1) Discrete-Event Simulation (DES)

Discrete-event simulation is a mature simulation method [4]. Discrete-event simulation is one way of building up models as a top-down structure to observe time-based behavior within a system. Formal methods have been developed to build simulation models and ensure the models are credible [4]. Arena and Witness are two examples of discrete-event simulation tools [36, 37].

2) Agent-Based Simulation (ABS)

Agent-based simulation is a relatively new but fast developing simulation method [38, 39, 40, 41]. It is used to model and simulate complex industrial processes and scientific systems [42, 43]. Agent-based simulation method build up models as a bottom-up architecture [7, 38]. Agent-based simulation is becoming an important problem-solving approach for many existing and conceptual systems [41, 43, 44].

Agent-based simulation tools include, but are not limited to: NetLogo [45], Spread sheet, Repast, Starlogo, Swarm, Matlab, Mathematica, Anylogic [4, 5, 38, 41, 42], and others.

3.4. Key Features of Agent-Based Simulation

Agent-based simulation builds up models as bottom-up infrastructures. Agent-based simulation model involves a series of autonomous agents, which represent independent entities in a real-world system. Each agent has its own nature and characteristics that govern agents' behaviors and interactions within a simulation world. Simulation specifications implemented by programing code determine the primary nature and characteristics of the agents.

Agent-based simulation models possess typical patterns of modeling and simulation, i.e., "input – model – output". Input parameters are defined according to specific research interests, and displayed in an input section in NetLogo. Simulation outcomes are shown as outputs, by the means of either graphical curves or on a NetLogo information board. The operational scenario of the whole system is displayed in a simulation world that represents the real-world operational environment.

Agent-based simulation models are comprised of three primary components [27, 38]:

- A set of autonomous agents with independent characteristics and behaviors;
- A set of simulation specifications determining how and with whom agents act and interact; and
- A simulation world where agents act and interact with each other.

Within agent-based simulation model, autonomous agents act and interact with each other complying with specified simulation rules. Through micro-level individual agents' actions, behaviors and interactions, macro-level system

performance is displayed in a simulation world, and observed and analyzed by the model operator [38].

4. MAPPING BETWEEN AGENT-BASED SIMULATION AND NEW PRODUCT DEVELOPMENT PROCESS CONCEPTS

As discussed in Section 2, new product development processes have three primary characteristics. Firstly, they are comprised of a series of independent but interactive functional work teams [8]. Secondly, the functional teams work in a complex information communication system [2]. And finally, new product development processes operate in real world operational environment [46]. Macro-level system performance of new product development process is influenced and determined by the micro-level work teams' activities, behaviors and performance. These three essential aspects underpinning new product development processes are listed in Table 1.

Table 1 New product development process characteristics

NPDP	Characteristics
who	A series of independent but interactive work teams
what	Sharing, communicating and transforming product design and development data and information with each other
where	A real world operational environment

From Section 3, agent-based simulation comprises a set of independent and autonomous agents that act and interact with each other [27, 38] complying with simulation rules in a simulation world. When interacting with each other, agents share, communicate and transform available information in the simulation world. Macro-level system performance is influenced and determined by micro-level individual agents' behaviors and performance. These three characteristics of agent-based simulation are summarized in Table 2.

Table 2 Agent-based simulation characteristics

ABS	Characteristics
who	A set of autonomous agents with independent nature, behaviors, and decision-making
what	Autonomous agents act and interact with each other complying with simulation specifications, to share, communicate and transform information and data
where	A simulation world within simulation model

It can be seen that, with this perspective on new product development processes, both new product development process and agent-based simulation have similar architectures. This research investigated the application of agent-based simulation method to better understand the nature and performance of a case study new product development process. The mapping between key concepts from the two that is shown in Table 3 was established as part of the research.

Table 3 shows mirror relationships between agent-based simulation and new product development processes. With respect to the established simulation mapping, functional work teams involved in new product development processes can be represented by individual autonomous agents in agent-based simulation models. Activities and behaviors of work teams in a real-world operational environment can be implemented by actions and interactions of autonomous agents in a simulation model complying with specified simulation specifications. Finally, the simulation world, where autonomous agents act and interact with each other, can be used to mimic new product development process operations in a real-world environment.

Table 3 Simulation mapping

	New Product Development Process	Mirror relationship	Agent-Based Simulation
who	independent functional work teams	⇔	independent autonomous agents
what	communicating product design and development information and data with each other	⇔	sharing, communicating and transforming information and data with each other
where	a real world operation environment	⇔	a simulation world in simulation model

5. SIMULATION CASE STUDY

This research used a new product development process case study in a large UK-based manufacturing company. In this section, the case study new product development process is demonstrated, and an agent-based simulation model is developed to mimic its operation.

5.1. New Product Development Process Case Study

The case study new product development process includes four stages (work teams): preliminary design, detail design, manufacturing and service. Fig. 5 illustrates the case study new product development process.

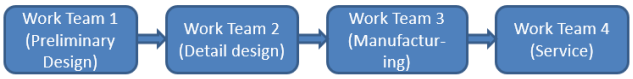

Fig. 5 Case study new product development process

The four work teams' design commissions are explained as follows. Preliminary design is responsible for customer requirements surveys, technical analysis, product concept generation, and so forth; it delivers selected design concepts to the detail design team. Detail design develops one or more selected concepts, to produce designs that comply with technical standards and specifications, manufacturing capability, and other requirements. A final design is approved and passed to the manufacturing team which makes, assembles and tests the product. The manufactured product is supplied to customers; the service team launches products and provides through-life support.

At the beginning of the development process, the preliminary design team requests information support from the detail design team, and the detail design team provides responses to such requests; this forms an information loop of requests and responses. However, the detail design team often does not have the resources to prioritize responses quickly enough for the preliminary design team to deliver design concepts to schedule. Under these circumstances, the information loop is broken which results in uncertainties and risks within the system. The same pattern also occurs between other stages. In the case study new product development process, each work team uses information and

data from other teams, and at the same time provides information to other teams, which forms a complex information intensive engineering operation system.

The research focused on understanding design information communication and transformation in the process. This involved examining design iterations caused by broken information loops, and quantifying the time resource used for rework due to incomplete design information within the process. The research aim was to investigate key features of new product development processes, with a view to identifying management intervention strategies that could shorten product development cycles and increase product development efficiency and effectiveness.

5.2. Agent-Based Simulation Model

With respect to the simulation mapping established in Section 4, an agent-based simulation model was developed using the NetLogo platform. A screenshot of the simulation world in the simulation model is displayed in Fig. 6.

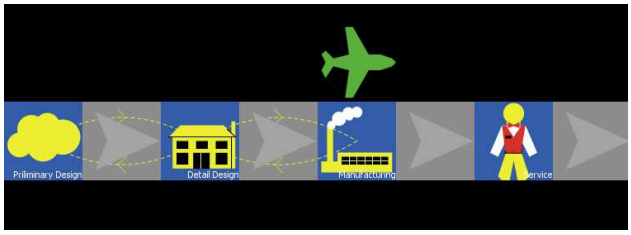

Fig. 6 Agent-based simulation model interface

Autonomous agents involved in the simulation model represented different work teams within the process: the cloud icon represents the preliminary design team, the building icon represents the detail design team, the factory icon the manufacturing team, and the technician icon the service team. The airplane icon represents the product that the teams worked with.

In the simulation model, different autonomous agents represent distinct work teams in the new product development process. With respect to the real-world operational situation, in the case study new product development process, each agent was designed with specific simulation specifications that governed its activities and behaviors in the simulation world. When the simulation model runs, full details of design and development activities, behaviors, interactions and decision-making are visualized in the simulation world.

6. CONCLUSIONS AND FUTURE WORK

New product development processes comprise a series of functional work teams that transform a design commission into physical products within a complex information communication system. Agent-based simulation comprises a set of autonomous agents that act and interact with each other complying with simulation specifications in a simulation world. An agent-based simulation mapping to key characteristics of new product development processes was established. The simulation mapping demonstrates mirror relationship between the main elements of new product development processes and key concepts that underpin agent-based simulation. The simulation mapping provides a conceptual foundation for the application of agent-based simulation methods to the investigation of complex socio-technical systems such as new product development processes.

A case study new product development process was introduced towards the end of the paper. An agent-based simulation model was developed to represent the real-world operation system. Results showed agent-based simulation to be a promising approach to study product new product development process, and examine its performance.

Future work includes three aspects: 1) exploring agent-based simulation capabilities to support operational management in new product development processes; 2) applying artificial intelligence technology in agent-based simulation models to optimize decision-making processes in new product development processes; and 3) applying agent-based simulation to investigating organizational features, decision-making mechanisms, and factors that influence the performance of new product development processes. The ultimate goal of the research is to present an artificial intelligence agent-based simulation management tool for industrial operations management in new product development processes in order to cost-effectively organize enterprise resources, such as time, financial budgets and human resources.

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Alison McKay is Professor of Design Systems at the University of Leeds and director of the Leeds Socio-Technical Centre. She holds a PhD in Mechanical Engineering. Her research centres on socio-technical aspects of engineering design systems and the networks of organisations that both develop and deliver products to market, and support them through life to disposal or reuse. The focus of her personal research lies in the establishment of systematic and, where possible, well-founded underpinnings for such systems, in particular, for the definition of product data.