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A Comparison of Discrete-Event Simulation Approaches for Complex Manufacturing Systems and Healthcare Systems

Ein Vergleich von Ansätzen der diskreten Simulation für komplexe Produktionssysteme und für Systeme im Gesundheitswesen

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Abstract: In this paper, we compare discrete-event simulation approaches for complex manufacturing systems and healthcare systems. The aim of this paper is to explore differences in simulation of complex manufacturing systems and healthcare systems as a first step to improving simulation of healthcare systems. We are interested in identifying obstacles and challenges for simulation application in healthcare systems. We focus on applications of discrete-event simulation to mainly address operational questions. We describe the manufacturing and healthcare domains, review the relevant literature, describe our research approach, point out the major structural differences in these domains, identify how these structural differences lead to modelling differences, and highlight some challenges in simulating healthcare systems.

1 Introduction

Discrete-Event Simulation (DES) has a long tradition in manufacturing. A large number of researchers have worked on this topic for decades. DES is used to design, understand, and improve manufacturing systems. Successful applications exist for different types of manufacturing systems (Negalban and Smith 2014). While there are still grand challenges (Fowler and Rose 2004), DES is in a relative mature state in the complex manufacturing domain.

Healthcare is now the world's largest industry. Compared to manufacturing, a smaller number of researchers have worked in simulation for healthcare for a long time (Günal and Pidd 2010 and Jacobson et al. 2013 and the references therein). On the one hand, there is an increasing interest in healthcare topics in the last decade. On the other hand, it seems that in contrast to the complex manufacturing domain, simulation techniques have not found their full way to hospitals very often (Kirchhof

and Meseth 2012 for the results of a survey dealing with applications of simulation in German healthcare institutions).

The main goal of the present paper is to explore differences in simulation of complex manufacturing systems and healthcare systems as a first step to improving simulation of healthcare systems. We are especially interested in identifying obstacles and challenges for simulation application in healthcare systems. Due to space limitations, we focus on applications of DES to address operational questions.

This paper is organised as follows. In Section 2, we briefly describe the two different domains. We then discuss related literature with respect to comparing DES techniques for these domains and describe our research approach. The comparison of the two domains is performed in Section 3, and major differences in modelling of the two domains are identified in Section 4. Specific challenges for simulating healthcare systems are discussed in Section 5. Finally, we provide some concluding remarks and mention a couple of areas for future research.

2 Problem Setting and Related Work

2.1 Domain Description

2.1.1 Complex Manufacturing Systems

Manufacturing systems have the purpose to produce goods. A manufacturing system consists of a base system and an information system. The system components of the base system are used to transform raw materials and intermediate products into final products. The information system and the corresponding planning and control processes are responsible for making planning and control decisions related to the production of goods.

The base system of a manufacturing system can be further divided into a job processing system and a material flow system. The job processing system contains all the system components that allow for value-added processing of working objects. Jobs are the most important working objects (i.e. entities). They are formed based on customer orders or forecast information. They are released into the manufacturing system after formation. Capacity for processing is offered by the system components of the job processing system. The job processing system is formed by resources including machines, operators, and auxiliary resources. The facilities that are used to store, transport, and supply raw material, working objects, and auxiliary resources form the material flow system. The base process in a manufacturing system is responsible for the usage of system components of the base system by working objects. The base process is specified by process flows, also called routes (sequences of operations), and a given set of working objects. A set of possible machines is assigned to each operation within a route.

Complex manufacturing systems are characterised by a number of specific process restrictions including a large number of products and routes that involve a large number of process steps. Resource flexibility is also typical, i.e., machines that offer the same functionality (parallel machines), are organised in machine groups. In addition, sequence-dependent setup times and batch processing machines exist. A batch is a set of jobs that are processed together at the same time on a single

machine. Frequent disturbances like machine breakdowns are also common. Semiconductor wafer fabrication facilities can be considered as complex manufacturing systems (Mönch et al. 2013).

2.1.2 Healthcare Systems

Healthcare systems deal with health diagnosis, treatment, and prevention of disease, illness, and injury of human beings. Similar to a manufacturing system, a healthcare system can be divided into a base system and an information system. The system components of the base system are given by system components that are responsible to provide care to patients. Patients are the working objects in healthcare systems. In contrast to jobs in manufacturing, patients have preferences with respect to be served by specific individuals, to be seen at a specific place, and to be seen at a specific time (Hall 2012). The base system can be differentiated in a subsystem that tries to control and improve the health status of patients, while there is another subsystem that deals with the transport of patients, supplies, and implantable devices, and organs. The base process in a healthcare system is responsible for the usage of resources by (or for) patients. It is represented by a sequence of subtasks that specify how to use the resources in specific situations by a set of patients. Care is provided through the provision of resources that have to meet the needs of the patients. Important resources in healthcare include doctors and other health professionals, different type of rooms, equipment, instruments, medical supplies, and implantable devices and organs (Hall 2012).

The basic components of a very simple queuing system in manufacturing and healthcare are shown in figure 1. Examples of resources and working objects are given. The healthcare system-related entities are marked in bold. We see that the principle structure of complex manufacturing and healthcare systems are similar.

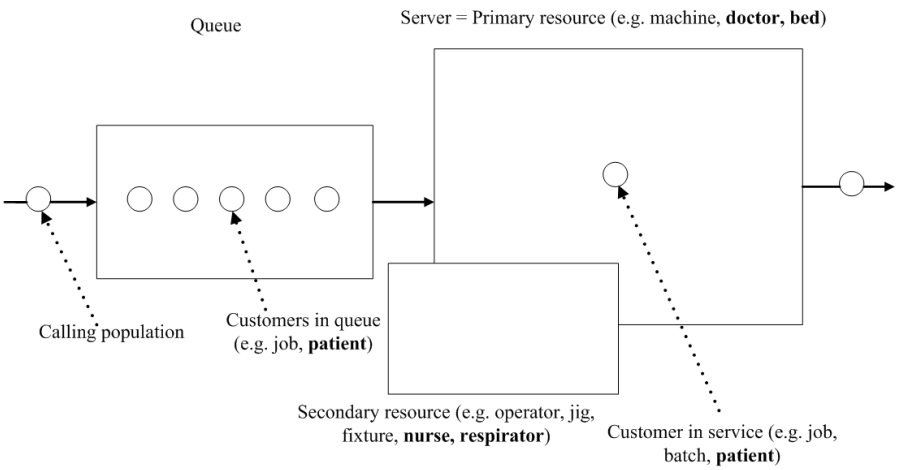

Figure 1: *Elements of a simple manufacturing or healthcare system*

2.2 Discussion of Related Literature

Next, we discuss related work with respect to DES approaches in healthcare and with respect to attempts to transfer knowledge from the manufacturing to the healthcare domain. There are many papers that deal with specific applications of DES in healthcare systems. Several recent surveys related to applications of discrete-event simulation in healthcare exist. Günal and Pidd (2010) discuss specific healthcare applications that are supported by simulation. Jacobson et al. (2012) provide a taxonomy of literature related to DES over the past 30 years.

Some researchers deal with transferring knowledge from other domains to healthcare. The possibility to transfer methods from job shop scheduling to appointment scheduling in healthcare is discussed by McKay (2011). Naseer et al. (2009) discuss the possibility to transfer knowledge from the defense domain to healthcare. The authors conclude that healthcare lags behind other domains, especially in terms of stakeholder engagement and in terms of implementation of simulation outcomes. Jahangirian et al. (2012) conduct a simulation-related literature analysis for the commerce, defense, and healthcare domains. Their findings are somewhat similar to those from Naseer et al. (2009). Verification and validation tasks are compared by means of case studies for the manufacturing and healthcare domains in Jenkins et al. (1998). The authors argue that healthcare is characterised by a level of complexity in handling resources in simulation models which does not often occur in the manufacturing domain. Kujlis et al. (2007) collect arguments for and against a possible transfer of methods from manufacturing to healthcare. The main findings of this paper are that methods from business and manufacturing are potentially applicable to healthcare, but their practical application is not straightforward because of the diversity and unique attitudes of the human actors involved in healthcare systems (Kujlis et al. 2007). Tako and Robinson (2012) conduct a survey to answer the question whether or not simulation in healthcare is different and more difficult than in other domains.

2.3 Research Approach

In the present paper, we are interested in comparing DES approaches for complex manufacturing and healthcare systems. The scope of the comparison is limited to discrete manufacturing systems because for this class of manufacturing systems we see some analogy to healthcare systems where the individual patient is modelled. We focus on applications of DES to mainly address operational questions. While we are aware of other simulation paradigms for healthcare systems including system dynamics, Monte Carlo simulation, agent-based simulation, or hybrid approaches (Brailsford et al. 2009), DES techniques are attractive for operational questions because this simulation paradigm allows for high-fidelity models. By analysing the comparison results, we strive for identifying obstacles and challenges for applying simulation in healthcare systems.

While there are several attempts made in the literature to discuss the differences of simulation approaches for the manufacturing and healthcare domain (see Subsection 2.2), to the best of our knowledge a clear comparison of the two domains based on analysing the differences in the underlying base systems and processes is missing.

3 Comparison of Complex Manufacturing and Healthcare Systems

3.1 Criteria for Comparison

We derive criteria for comparison from the domain description in Subsection 2.1. Therefore, we compare the base system and process and the related planning and control processes. This approach is reasonable since the abstract structure of the different subsystems and processes is somewhat similar for complex manufacturing systems and for healthcare systems. The specific criteria are shown in table 1. Note that we do not further differentiate between the information system and the corresponding information process. For comparison purposes, we are more interested in the related planning and control processes that describe under which circumstances specific control actions are carried out, while the information system that contains human decision-makers and application systems is responsible for providing planning and control instructions.

Table 1: *Criteria for comparing complex manufacturing and healthcare systems*

Subsystem/Subprocess	Criterion
Base system	resource types
	offered capacity
	reliability and maintenance policies and procedures
	emergency events, e.g. resource breakdowns
Base process	working objects, i.e. moving entities
	product vs. service structure and the resulting routes vs. sequences of subtasks
	nature of demand
	consumed capacity
	importance and impact of cycle time
	emergency events, e.g. patient emergencies
Information system/process	decision-making procedures

3.2 Results of the Comparison

3.2.1 Base System

We start by describing the different resource types as the main ingredients of the base system. In complex manufacturing systems, we have consumable resources, i.e. raw material, and renewable resources including machines and operators. Resources are used for job processing and material handling. There are auxiliary resources like photolithography masks in semiconductor manufacturing or jigs in mixed-model assembly lines in the aerospace industry. There is often a high degree of automation in complex manufacturing systems. Therefore, operators are often less important.

In healthcare systems, resources are responsible for patient treatment and transportation tasks. Important resources are different types of rooms, for instance, for examination, procedures, surgeries, diagnostic tests and recuperation. Equipment, e.g., a CT scanner, is either permanently or temporarily assigned to an operating room or an examination room. Instruments form another important class of resources since they support medical procedures. Examples of instruments include thermometers and surgical instruments. Another class of resources is given by human resources such as doctors and different types of nurses. The human resources often have multi-tasking capabilities in time and space. For instance, a nurse might be responsible for several patients at the same time even though the patients stay in different rooms. Doctors and nurses perform direct patient care activities when they treat a patient. However, at the same time, indirect activities interrupt direct activities. Examples of indirect activities are given by writing or reading the file of a patient, discussing the status of a patient with a colleague or the family of the patient, and cleaning the operating room and supplying it with new medical supplies and instruments. In contrast to manufacturing, healthcare personnel have some independency that allows them to choose the next task to be performed on their own.

Supplies including medications and blood, are items that are consumed when care is delivered. Implantable devises and organs, for instance a liver or a kidney, are required for certain medical procedures. The implantation procedure cannot start until the device or organ is available.

The different resources in healthcare systems have to be often strongly synchronised in such a way that the requested resources are available when the patients need them. This includes the right amount and type of resources. For example, most surgeries cannot start if an anesthesia doctor or a surgical nurse is unavailable. The different types of resources found in both domains are summarised in table 2.

Table 2: *Resources in complex manufacturing and healthcare systems*

Renewable resource	Manufacturing	Healthcare
Primary	Machines (stationary)	medical doctors (mobile), operating rooms (stationary), equipment and instruments (mobile or stationary)
Secondary	Operators (mobile), auxiliary resources (often mobile)	anesthesia doctors (mobile), various types of nurses (mobile), equipment (mobile or stationary)
Tertiary	maintenance staff (mobile)	N/A
Consumable resource	raw materials	medical supplies, implantable devices, organs

Next we discuss the offered capacity in both domains. The capacity of resources in manufacturing systems is given in parts (jobs) per hour. Usually, capacity modelling is difficult in manufacturing (Elmaghraby 2011). The rate when the resources are available is variable since machine breakdowns occur quite often. In healthcare,

capacity is given in man hours available. The rate when resources are available is generally relatively constant.

The reliability of machines in complex manufacturing is often rather low. Machine-related emergency events, i.e. machine breakdowns, occur quite often. Therefore, various kinds of preventive maintenance policies exist in manufacturing plants. The maintenance activities consume scarce capacity. In healthcare systems, however, the reliability of resources is usually much higher. Equipment breakdowns are generally not a major source of difficulties. The preventive maintenance policies for equipment are different compared to manufacturing. The related activities usually do not reduce the capacity because they are performed outside regular working hours.

3.2.2 Base Process and Decision-making

Jobs, also called parts, are the working objects in complex manufacturing systems. Important attributes include the priority of the job, its size, and its due date. Quality-related attributes also occur quite often. The specification of how to manufacture a part, i.e. its route, is given by the corresponding product specification. The manufacturing of a specific product often requires assembly activities as described by the bill of materials (BOM). Assembly activities require a synchronisation of subparts.

In healthcare systems, however, a patient with a medical condition is the working object. The required speciality is a result of this medical condition. There are different types of due dates for a patient. We find patients with regular, urgent, and emergency due dates. Since the medical condition of a patient can change over time, certain attribute values like the temperature might also vary.

A product is well-defined through a set of BOMs and routes. It is relative static, i.e., the product specification does not change often. However, we find sequence, process, and resource (machine) flexibility to manufacture a product. The amount of operations to be performed is often large. For instance, up to 800 process steps are required in semiconductor manufacturing to produce a single integrated circuit. The manufacturing process has to follow the product specification closely.

In healthcare, we do not find a static product description. Each medical condition (there can be more than one medical condition for a single patient) requires a specific service (or set of services). Each service might require subservices. On the one hand, the sequence of these subservices is often unknown in advance. On the other hand, the number of subservices is rather small compared to complex manufacturing. The offered flexibility in healthcare is much smaller than in manufacturing. We find almost no process flexibility and only some sequence and resource flexibility.

The demand in manufacturing is often levelled even though it might be unpredictable. However, because of order release mechanisms, inventory, and backlog handling strategies, we know with more certainty which requests will arrive on the shop floor. In contrast to manufacturing, the demand is unlevelled in healthcare. In the long term it may follow a specific pattern, for example, it might depend on the day of the week or it might be based on the population size. However, in the short term demand in healthcare is highly unpredictable. Inventory strategies through preproduction are almost impossible. The demand situation in emergency rooms is quite different from the one in outpatient clinics. Therefore, the character of the medical facility or the hospital unit is important to describe the nature of demand.

From a consumed capacity point of view, in manufacturing systems we observe relatively low arrival variability (see the demand discussion above). The amount of consumption generally has a low or medium uncertainty. On the other hand, we find rather high arrival variability in healthcare systems. This arrival variability goes along with a highly uncertain amount of consumption (e.g. two patients with the same medical condition may require a significantly different length of stay).

In manufacturing, cycle time is defined as the amount of time elapsing between work being released into the manufacturing system and its emerging as finished product that can be used to meet demand. In healthcare, the counterpart of the cycle time is the time span between the arrival of a patient and his or her departure. The amount of cycle time ranges from days to several weeks in complex manufacturing, while in healthcare a cycle time of minutes, hours, or days is more typical.

Emergency events like emergency patients occur quite often in healthcare systems. High-priority jobs, so called hot or rocket jobs, are common in many manufacturing settings. But they are not really a counterpart to emergency patients since their appearance is less uncertain and are not a matter of life and death.

Operational decisions in complex manufacturing are often heavily influenced by previous decisions because of the complex product structure and the rather long cycle times. The impact of previous decisions is much smaller in healthcare systems. Subproblems based on time decomposition, for example appointment scheduling for a single day, are not heavily coupled.

4 Identification of Major Differences in Modelling

The following modelling differences are identified based on the results of the comparison performed in Section 3:

1. As Jenkins et al. (1998) point out "the health sector is characterized by a level of complexity in handling 'resources' (as understood in simulation modelling) which is not frequently found in the manufacturing sector". While in manufacturing activities can be modelled as happening at discrete points of time and the machines are often the most important resources, in healthcare the modelling of secondary resources is generally more important. Multi-tasking abilities often need to be modelled, e.g. nurses may monitor many patients at the same time. While it is possible to crudely model these activities with a discrete modelling paradigm, it may not be adequate to capture their impact for a high fidelity model.
2. The modelling of human behavior is generally more important in healthcare compared to complex manufacturing. Three things make the modelling of human behavior in healthcare particularly challenging: 1) many activities involve multiple humans who act independently (cf. Lim et al., 2013); 2) healthcare providers are involved in many indirect activities that are typically not modelled resulting in underestimation of patient waiting times (cf. Rohleder et al., 2011); and 3) patients sometimes make irrational make choices that impact their future health (cf. Brailsford and Schmidt, 2003).
3. The dynamic nature and composition of services and subservices in healthcare is very different from the rather static product and route structure in most manufacturing systems. In the survey by Tako and Robinson (2012), 66% of the

respondents indicated that they felt there was "less evident structure" compared to other domains.

4. For the working objects in healthcare (i.e. the patients), the modelling of entity attributes is generally more important and more difficult because they are not known ahead of time and they might change over time (e.g. the patient temperature).
5. Unexpected or emergency events have a different sense of urgency in manufacturing and healthcare settings (life or death) and may require different treatments.

5 Challenges for Healthcare Simulation

The following challenges exist for modelling and simulation of healthcare systems:

1. The modelling of primary and secondary resources needs to be improved in simulation models for healthcare systems. We believe that hybrids of continuous, discrete-event, and agent-based simulations are a fruitful avenue for further exploration.
2. The modelling of human behavior needs to be better incorporated in simulation models. Some initial steps towards this goal are described by Brailsford and Schmidt (2003). One way to reach this goal might be the usage of agent-based simulation techniques.
3. Compared to complex manufacturing, there is a larger need to model the stochastic behavior of resources and working objects.
4. In contrast to manufacturing, healthcare simulation models are generally smaller in spatial and time scope. At the same time, the more complicated service structure of healthcare is a serious modelling issue.

6 Conclusions and Future Research

In this paper, we discussed the commonalities and differences in simulating complex manufacturing and healthcare systems. By differentiating between base system and process and information system, we were able to derive criteria to conduct such a comparison. Our main findings were that there are a couple of important differences. The modelling of resources is generally more sophisticated in healthcare simulations. The composition of services in healthcare is quite different from the more static product structure and route definition in complex manufacturing systems. The simulation models in healthcare are often smaller in size and need more details compared to the large-scale simulation models in complex manufacturing. This is not to say that healthcare systems cannot be adequately modelled using DES constructs very similar to those used for manufacturing systems for some applications, but refinement of these techniques or other approaches may be needed to achieve high fidelity models.

There are some directions for future work. First of all, we are interested in completing the discussion in this paper by considering simulation paradigms different from DES including system dynamics and agent-based simulation. We propose to look at simulation applications at a more strategic level rather than focusing only on the operational level. Secondly, while in the present paper simulation is primarily used to represent the base system and process of the underlying system, it seems

interesting to compare the usage of simulation for decision-making, i.e. simulation is part of the planning and control system.

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