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USING SIMULATION MODELS AS EARLY STRATEGIC DECISION SUPPORT IN HEALTH CARE - DESIGNING A MEDICAL 3D PRINTING CENTER AT POINT OF CARE IN HOSPITALS

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ABSTRACT

We present a scalable simulation model of a medical 3D printing center at point of care, which is used for early strategic decision making concerning its configuration. The model is part of an ongoing research initiative where 3D printing technology is designed and assessed for the purpose of producing patient specific medical devices at point of care. The model captures uncertainties in medical 3D printing technology, resulting yield, maintenance, clinical process, and organizational factors. Based on a set of defined scenarios capturing current and future demand including ramp up phases the model's performance can then be evaluated and used for estimating associated requirements and operational performance. We present the model itself, its underlying simplifications and assumptions as well as input data and several scenarios. The results and their impact on strategic decisions will also be discussed.

1 INTRODUCTION

The application of modeling and simulation is a well-established approach for analyzing and designing processes in health care (Brailsford et al. 2009). Compared to industrial engineering applications, health care provides some additional challenges, because of complex and complicated diagnostics and treatment pathways and a mainly patient-centric view (Roy et al. 2020). Nevertheless, treatments and diagnostic processes are highly standardized and well defined both in quality and performance. Therefore, there are many success stories of modeling and simulation in health care (e.g.: Salleh et al. (2017)).

In this paper we describe the use of modeling and simulation for generating support for strategic decisions about the application of new technologies in the context of a large, international, and interdisciplinary research project on the application of additive manufacturing in health care (Medical University of Graz 2021). A center for 3D printing in a clinic with all its core processes needs to be drafted at a very early stage to ensure sufficient infrastructure resources for later operations as well as to generate input for business case calculations.

The main idea is to use 3D printing technology for on-demand generation of personalized, perfectly fitting, implants directly at the clinic. These implants could be used for treatment of fractures and/or lesions caused by trauma or tumor infiltration. Such a technology could replace the often improvised usage of

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sub-optimal implants in emergency care. On the patient side this could also avoid a second surgery, caused by long delivery times for especially produced implants from external commercial suppliers.

The entire printing process exposes a high variability in demand and technology-based variance in supply at the current state: While 3D printing (metal, polymers as well as ceramics) has been established as a useful additive manufacturing technology in industry, applications in health care are still in a very early research state. There are three main reasons for that: one lies in the increased hygienic requirements regarding surface, tightness, porosity of the printed implants which could lead to lethal immune reactions – in the worst case. Another reason is the narrow selection of certified bio-compatible materials meeting both mechanical and technological requirements for 3D printing. The third reason is due to the fact that correct measuring and designing the implant physiologically correct is difficult, which may lead to several iterations depending on type and nature of the medical emergency for which the implant is needed. All these factors lead to a high variance in productivity and quality of such a production.

Currently the demand for 3D printed implants in the clinic is only driven by a few technicians and interested surgeons at a research level, which leads to a rather small and varying demand. Based on preliminary promising results of the research initiative, a steep increase in demand can be expected.

Since we are initially operating in a very data-poor environment with many unknowns, and uncertainties (like processing times, utilization and demand, technology, etc.) we create a scalable, applicable for small and large 3D printing centers e.g. easy to add more printers or any other type of resources, and configurable, e.g. easy to change type of materials, printers, and products, simulation model in collaboration with involved medical stakeholders. Further, we define simulation scenarios which reflect different configurations of resources (3D printers, employees, tools, IT-workstations, etc.) and allow for the assessment of the performance for current and future operations.

While simulation in health care operations is often used at a very mature stage with already well defined processes and procedures, we use a scenario-based approach at a very early stage to gain first insights on using a new technology and estimating its potential for daily clinical use. Discrete Event Simulation (DES) (Brailsford and Hilton 2001) is applied to simulate the currently defined manufacturing process on an operational level. The simulation model is capable of providing long term operational data that can be used to support early strategic decisions such as the dimensions of the future 3D printing center. The simulation results for the defined scenarios can also be used for estimating their potential operations performance and required resources. Furthermore, by combining both factors it may also be possible to decide on the economic feasibility for daily clinic operations.

This paper is organized as follows: Section 2 describes the context of this research. In Section 3 further information on simulation in the respective area, 3D printing, and its application in health care is given. Section 4 describes the conceptual model of a medical 3D printing center. Section 5 provides an overview of the defined scenarios for the evaluation. In Section 6 the results of all scenarios are presented. Finally, Section 7 discusses the results, as well as limitations, and provides an outlook for further research.

2 CASE STUDY DESCRIPTION AND MOTIVATION

The research project ”CAMed - Clinical Additive Manufacturing for Medical Applications” (Medical University of Graz 2021), which provides the context of this research, is aiming to develop the entire process chain to enable 3D printing at point of care and thereby focuses on research areas such as novel materials, printing technologies, clinical evaluation, and IT and process integration. CAMed aims to improve patient outcomes by personalized medicine in form of 3D printed patient specific implants, anatomical models and tools at point of care. Improved patient outcomes for example can be attributed to reduced duration and even reduced numbers of surgeries. An internal 3D printing research lab was initiated at the LKH University Hospital Graz to enable a future in-house production. This CAMed 3D printing research lab is used as basis for data generation in this work. This work investigates the in-house production of 3D printed patient specific implants, anatomical models and tools from an operational point of view. A simulation model was created to provide a basis for answering strategic questions regarding the operation of a medical 3D printing center already in an early research and development phase. The research should foster strategic decision making for hospital organizations, which aim to operate a medical 3D printing center on an operative day to day basis.

The model enables to simulate various aspects and scenarios of a medical 3D printing center and thereby supports quantitative reasoning about economic future scenarios. It considers aspects such as resources (human, IT, machines), process duration, shift-plans, and technological future developments for the manufacturing of the three product types patient specific implants, anatomical models, and tools. The currently existing CAMed 3D printing research lab and first insights gained in operational details during the research project serve as a basis. The model also considers general known operative effects such as increasing learning curves during ramp-up of production and represents the core manufacturing process, pre- and post processing of the manufactured part, and also supportive processes such as repair and maintenance of printers and material handling (ordering and storing) processes. The following aspects are aimed to be answered by the model:

- Which maximum output of manufactured items is possible based on the current setup of the CAMed 3D printing research lab?
- How do the various aspects such as resources (human, IT, machines), process duration, shift-plans, and technological future developments influence the performance of a medical 3D printing center?
- How does the medical 3D printing center need to be dimensioned, based on expected demand scenarios?
- Which service levels in terms of throughput times and quantities can be derived from the insights gained with the simulation during ramp-up and operational phase of the medical 3D printing center?
- How does the consideration of learning curves (e.g. improved order process, improved maintenance and operation processes) during the ramp-up phase affect the operations and in consequence the output of the medical 3D printing center?
- How does the production system react on increased demands and what are the consequences for key performance indicators (KPIs) such as throughput times and workloads of various resources (e.g. 3D printers, test equipment, workloads of persons)?

3 RELATED LITERATURE

Modeling and Simulation is a commonly used tool to analyze and improve health care services. For exhaustive reviews the interested reader is referred to Brailsford et al. (2009), Günal and Pidd (2010), Pitt et al. (2016), or Roy et al. (2020), whereas Salleh et al. (2017) provide an umbrella review on existing reviews. According to Günal and Pidd (2010) applications of health care simulations can be classified in Accident and Emergency (A&E) models, e.g. Furian et al. (2018)), outpatient clinic models, e.g. Norouzzadeh et al. (2015), inpatient facilities, e.g. Harrison et al. (2005), and other hospital units, as for example laboratories, operating theaters or screening units. For examples the reader is referred to Günal and Pidd (2010). The model of the printing center studied in this paper may best be assigned to the last category, as it provides auxiliary services tor primary care services in a hospital environment. For additional studies on Modeling and Simulation in the context of 3D printing in other domains the reader is reffered to Jia et al. (2016) and Khajavi et al. (2014).

According to Robinson (2006) Conceptual Modeling has high significance in a simulation study in general. And particularly in this work as the real system doesn't exist yet. Therefor a structured approach for defining the conceptual model was required. The Hierarchical Control Conceptual Modeling (HCCM) framework by Furian et al. (2015) serves this purpose and was therefore applied to design the non-software specific conceptual model including all decisions and the logic of the 3D printing center. The HCDESLib by Furian et al. (2016) is based on the structure of the HCCM framework and was used to implement the conceptual model. Further applications of DES on comparable systems such as blood donation centers or blood laboratories are described by Doneda et al. (2021) and Kadı et al. (2016).

The additive manufacturing technology (3D printing) has reached a high level of maturity in various industrial domains and is considered an established, reliable and future-oriented technology. This has already been shown in many areas of application (Gao et al. 2015; Attaran 2017). 3D printing has also great potential in the medical domain by providing many new possibilities in terms of materials, shapes, etc. for the individualized and fast manufacture of medical devices. However, these newer fields of application in medicine pose special challenges to the use of this technology due to the higher requirements for medical devices in terms of bio-compatibility, safety and particular mechanical properties. Currently, various projects and initiatives foster research and development in this area (Mayo Clinic 2021; Jacob et al. 2020; University Hospital Basel 2021; Scholer 2019). 3D printing is being utilized in many medical applications, particularly for patient specific medical devices (Eshkalak et al. 2020). Such applications are the production of patient specific implants (Memon et al. 2020; Sharma et al. 2020; Willemsen et al. 2019) or the production of anatomical models for pre-operative planning (Leng et al. 2017; Punyaratabandhu et al. 2018; Ballard et al. 2020). For an overview of the various fields of application the reader is referred to Nadagouda et al. (2020).

4 MODEL DESCRIPTION

This section describes the conceptual model of a medical 3D printing center. The conceptual model was created following the HCCM framework (Furian et al. 2015). The design of the conceptual model is based on the CAMed 3D printing research lab (Medical University of Graz 2021). First, an overview of the system including modeled entities, their individual behavior, and defined control structures is given. Next, the inputs and outputs of the model are explained. Finally, the applied simplifications and assumptions as well as the implementation, verification and validation of the model are described.

4.1 System Overview

The system overview (see Figure 1) illustrates the main production processes for manufacturing individualized 3D printed medical devices such as implants or anatomic models. The shown process is an aggregated version of the detailed business process. The process starts with arrival of orders and ends with the delivery of the product to the customer. The production process is structured in four main processes, which are: ”Request 3D Printed Product”, ”Manufacture 3D Printed Product”, ”Check Quality of 3D Printed Product”, and ”Sterilize and Deliver 3D Printed Product”. The manufacturing part of the process is further split into three main steps: ”Segmentation”, ”Modeling”, and ”3D Printing”. Whereas ”3D Printing” also includes the related post processing activities, such as the removal of support structures.

Each main process consists of various activities and requires certain entities for execution. These entities are orders, employees, 3D printers, materials, computer, software, tools, and working benches. The orders represent the demand of 3D printed products for the hospital. A demand growth can be applied to represent an expected economic growth of the business over time. Orders are treated in dependence of their priority. The priority is defined in three levels: urgent, normal, and low priority. Orders represent 3 types of products, which are patient specific implants, pre-operative anatomical models, and tools. The type of product determines if certain activities are required or not. For example, in our scenarios it is not required for anatomical models to be sterilized, as those anatomical models are not supposed to be used in the operating theater. Whereas it is required to sterilize implants. Furthermore, the type of product also determines the required material and therefore also the required 3D printer. In this model 3D printers are specialized for certain materials such as high or low temperature materials. Besides that, computers including various types of software are required. The types of software are represented as skills of a computer. For example a certain type of software is required to create a 3D model of the part to be printed. In addition to those, tools and working benches for post processing or maintenance activities are also represented as entities. Employees are currently structured in technical staff, radiology technologists, and quality managers. Each employee is assigned to specific activities, concerning his profession.

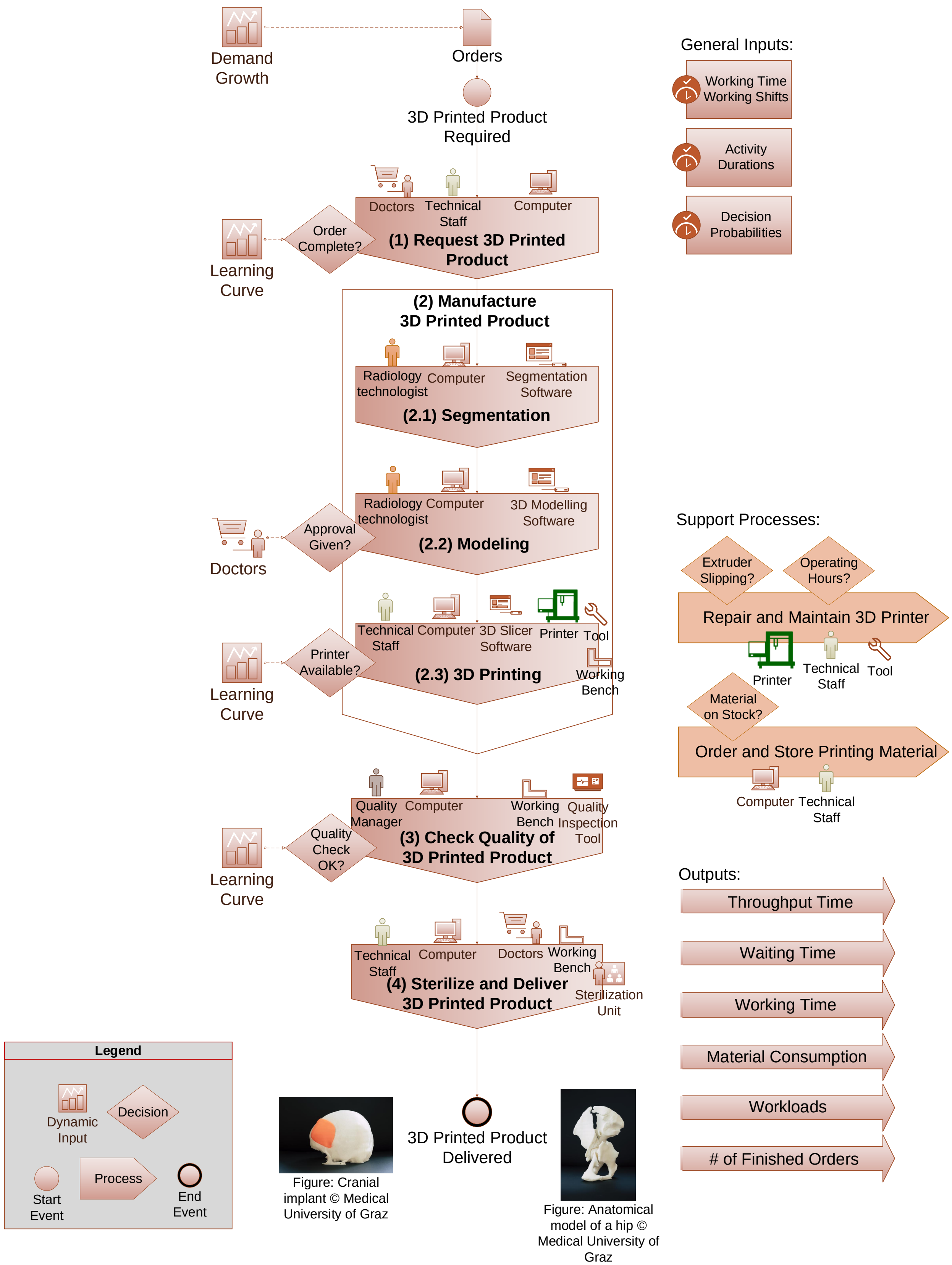

Figure 1: System overview of a medical 3D printing center.

The duration of certain activities are modeled with a distribution function to represent a realistic behavior. For example, the duration of repairing a printer is modeled with an exponential distribution function, to also represent exceptional situations that might take much longer than expected.

Relevant decisions throughout the production process such as ”Order Complete?” or ”Quality Check OK?” are modeled with probability functions and an optional ”Learning Curve”. This ”Learning Curve” should represent an organizational learning in terms of process mastery and minor technological improvements.

Besides the main processes also required support processes for repairing and maintaining the 3D printers and for ordering and storing the required printing material are included in the model and are triggered based on the availability and operating hours of the 3D printers.

4.2 Inputs and Outputs

Inputs have been defined in a way that allows high flexibility in the definition of scenarios and avoiding additional programming efforts. The inputs are grouped in general, resource specific and process related parameters (see Table 1).

Table 1: Overview of inputs for the simulation model.

Input Group	Input Type	Description	Input Values
General	Simulation time	Start date & time and end date & time of simulation.	Date & Time
	Type of product	Selection of predefined product types.	Implant, model, and tool
	Time between order arrivals	Defines the amount of orders per product type.	Hours
	Average weight of product	Defines a specific average weight of a certain product.	g
	Urgency: low, normal, high	Defines the priority of the order.	Percentage of urgency
	Demand growth	Defines the relative increase of orders per year.	Percentage per year
Resources	Employees	Defines amount of predefined types of employees	Technical staff, radiology technologists, and quality manager
	3D printer	Selection of amount, type, and availability of 3D printers including build up rate and material skills.	Name, type, and material skills
	Material	Defines amount and type of available materials.	Name, amount of units, unit size, min. amount on stock
	Computer	Defines amount of available computers.	Amount of computers
	Working Benches	Defines amount of available working benches.	Amount of working benches
	Tools	Defines amount of available tool sets.	Amount of tool sets
Process	Working Shift	Defines the start time and end time of a shift on a daily basis.	Start time, end time
	Activity Durations	Defines the duration of each predefined activity.	Minutes
	Decision Probabilities	Defines the probability of each predefined decision.	Percentage
	Learning Curve Parameters	Defines the start and end probability of predefined decision parameters: Availability of printer, order request complete, and quality check OK	Percentage

Outputs (see Table 2) are defined KPIs that should represent the performance of the medical 3D printing center. The outputs are calculated and aggregated during run-time of the simulation and reported in a structured output file.

Table 2: Overview of outputs of the simulation model.

Output type	Description	Output values
Total simulation time	Overall time of simulation run.	Hours
Total throughput time per product type	Throughput time for each product type.	Hours (average, median, min., max.)
Total working time	Overall working time in simulation period.	Hours
Total finished orders	Overall amount of finished orders.	Amount
Working times	Working times are calculated per activity and per produced part.	Hours (total, average, median, min., max.)
Waiting times	Waiting times are calculated per activity.	Hours (total, average, median, min., max.)
Workloads	Calculated for each resource based on overall working time.	Percentage
Material consumption	Usage of material in total and per produced part.	g
Material reorders	Amount of required material reorders.	Amount
Repair and maintenance efforts	Amount of repair and maintenance activities including required hours.	Amount and hours
Printer downtime	Relative downtime of each 3D printer.	Percentage
Printing time	Actual printing time of each 3D printer.	Hours
Order specific output	Printing time per order and working times of resources per order.	Hours

4.3 Simplifications and Assumptions

Due to an early stage of the CAMed research project and the novelty of the business following simplifications and assumptions are applied in the model:

1. Working days are Monday to Friday, vacations and sick leaves are not considered.
2. Breaks (e.g. lunch break) are not considered by the simulation.
3. Orders arrive during working time. If an order arrives at any other time it is rescheduled to to the start working time of the next working day.
4. The required material for an ordered part is defined by a mean value per product type and created with a Gaussian distribution.
5. The build up rate of a printer is based on empiric data from the CAMed 3D printing research lab.
6. The printing time is based on this build up rate and the required amount of material for the order.
7. The 3D printer repairs are based on their defined availability.
8. Printers can be repaired by technical staff, therefore no waiting times for external support are considered.
9. Already started activities, that would take longer than the defined working shift, will be finished. This situation is considered as overtime.

4.4 Implementation, Verification, and Validation

The conceptual model was implemented with the HCDESlib (Furian, Neubacher, Vössner, O'Sullivan, and Walker 2016). The implemented simulation model was verified with test scenarios by varying the input parameters and observing if the simulation model provides expected and logical outputs. Currently no detailed recordings of e.g. throughput times or any other outputs are available. In addition to that, the existing lab is only used for research purposes and doesn't represent a fully operational 3D printing center. (Paal 2020; Rosenzopf 2021)

The simulation model was validated by reviewing and discussing each scenario and the corresponding simulation outputs (see Section 6) with subject matter experts in a workshop. These experts are the technical leader of the 3D printing research lab, the managing director of the CAMed project and the scientific leader of the CAMed project. The simulation outputs were considered as reasonable based on their experience gained throughout the current operation of the research lab, especially for the baseline scenarios, which represent the current resources state of the 3D printing research lab.

5 SCENARIOS

This section describes all defined scenarios for the evaluation of the simulation model. Table 3 provides an overview of the used input parameters for each scenario. Following general constraints, based on discussion with domain experts from the CAMed 3D printing research lab, are applied to all scenarios. Only two types of printers are used. Each printer is capable of printing a certain material and therefore only capable of producing a certain product. Each shift is considered to be eight hours. The technical staff is also capable to conduct the quality inspection. The learning curve parameters are set as follows:

- Availability printer: Start value: 90%, end value: 95%
- Order request complete: Start value: 90%, end value: 98%
- Quality inspection of end product OK: Start value: 80%, end value: 98%

The baseline scenarios are defined in a way to represent roughly the current resources state of the CAMed 3D printing research lab. At a given demand, which is estimated based on current experiences by subject matter experts, it should set the performance baseline for the medical 3D printing center.

In the overload scenarios the demand is significantly increased to ensure that there is always a new order available. This should provide insights on the performance boundaries of the system. Further on, resources are increased to evaluate their impact on the performance.

The demand growth scenarios are a variation of the baseline scenarios. This scenarios should demonstrate the effect of a growing demand over time. It should help to identify at which point of time the KPIs such as throughput time increase significantly. This could indicate at which point of time it is required to invest in more resources to maintain the performance.

Finally, the specific evaluation scenarios deal with the goal to evaluate which technology and process improvements are required to achieve a certain throughput time. The targeted throughput time is based on clinical demands for the production of implants.

Table 3: Overview of scenarios

Scenario Group	Scenario	Simulation time [years]	Implant orders [#]	Anatomical model orders [#]	Learning curve	Demand growth [%/year]	Working shift [#]	High temp. printer [#]	Low temp. printer [#]	Technical staff / shift [#]	Radiology technologist / shift [#]	Computer [#]	Tools [#]	Working bench [#]	Throughput-time target [h]
Baseline	1_1	1	58	32	no	0	1	1	1	1	1	3	1	1	NA
	1_2				yes		1	1	1	1	1	3	1	1	
	1_3				no		2	1	1	1	1	3	1	1	
Overload	2_1	1	854	438	yes	0	1	1	1	1	1	3	1	1	NA
	2_2						2	1	1	1	1	3	1	1	
	2_3						1	2	2	2	2	6	2	2	
	2_4						1	2	2	1	1	3	1	1	
	2_5						1	1	1	2	2	3	1	1	
	2_6						3	1	1	1	1	3	1	1	
	2_7						2	1	2	1	2	3	1	1	
Demand growth	3_1	5	394	212	yes	10	1	1	1	1	1	3	1	1	NA
	3_2						2	1	1	1	1	3	1	1	
Specific evaluation	4_1	1	58	0	yes	0	3	1	1	1	1	3	1	1	24
	4_2						3	1	1	1	1	3	1	1	4

6 RESULTS

This section describes the results based on the outputs of the previously described scenarios. The outputs are based on the average of 200 simulation runs. Table 4 shows a selection of operational KPIs for different scenarios of the medical 3D printing center. The term ”Implant” refers to patient specific implants and the term ”Model” refers to anatomical models. The column ”Computer” only shows the value of the computer with the highest workload, except for scenario 2_3 (double resources), where the value for the computer with the second highest workload is also shown.

6.1 Baseline Scenarios

First the results of the baseline scenarios 1_1 - 1_3 are discussed. The comparison of 1_1 and 1_2 show that due to the learning curve the median throughput times drop by 0,5 days. Even though more orders can be finished, workloads can be reduced by 1 to 5%, depending on the resource type. Generally the learning curve reduces the throughput time of orders by 12 hours. With two shifts (1_3) the average waiting time

Table 4: Simulation results

		Avg. throughput time [days]		Median throughput time [days]		Min. throughput time [days]		Avg. working time [hours]		Workloads [%]				
Scenario	Avg. finished orders [#]	Model	Implant	Model	Implant	Model	Implant	Model	Implant	High temp. printer	Low temp. printer	Techn -ician	Radio-logist	Comp-uter
1_1	86	7,34	5,08	5,7	4,94	2,06	2,02	50,29	59,51	8	24	25	28	42
1_2	87	6,11	4,55	5,27	4,48	2,05	2,02	44,23	54,61	7	21	22	27	39
1_3	87	5,17	4,09	4,18	4,15	1,65	2,01	50,46	59,27	8	25	12	14	22
2_1	268	102,31	44,98	97,08	47,58	2,13	2,82	43,82	54,3	28	51	104	132	127
2_2	341	78,21	22,84	77,62	6,39	2,06	1,98	43,89	54,7	36	65	70	110	108
2_3	531	34,55	21,75	38,7	8,57	2,12	2,06	43,9	54,43	37 / 23	48 / 47	90 / 85	130 / 130	124 / 124
2_4	349	53,17	62,65	59,2	64,74	2,12	2,82	43,89	54,23	18 / 8	43 / 42	104	132	123
2_5	366	99,72	46,05	94,71	9,59	2,14	2,12	43,74	54,49	49	51	95 / 36	124 / 125	124
2_6	476	73,11	12,78	74,41	7,69	1,82	1,98	43,81	54,65	64	68	56	95	94
2_7	542	20,26	34,65	19,7	8,96	1,96	1,91	43,94	54,59	55	53 / 54	94	98 / 94	105
3_1	261	13,34	6,55	7,55	5,74	1,98	2,02	44,03	54,43	30	46	66	84	100
3_2	266	6,6	4,39	4,45	4,22	1,61	1,61	44,02	54,58	30	48	33	42	57
Implants only		Avg. throughput time [hours]		Median throughput time [hours]		Min. throughput time [hours]		Avg. working time [hours]		High temp. printer	Low temp. printer	Techn -ician	Radio-logist	Comp-uter
4_1	58	12,96		6,00		4,08		5,04		0,..	-	3	1	3
4_2	58	10,56		4,32		2,88		3,43		0,..	-	2	1	2

drops by 40 to 50 hours. The higher reduction of throughput time of anatomical models can be justified with the longer overall working and printing time. Whereas implants in our process always require 24 hours in sterilization, which is not required for anatomical models that are not supposed to be used in the operating theater in our scenarios.

6.2 Overload Scenarios

In the overload scenarios 2_1 - 2_6 the system boundaries including bottlenecks of the medical 3D printing center with different resources are examined. Here only orders with high priority are finished, which is also proving the correct dispatch order of the simulation model. The workloads above 100% arise from allowing overtime and calculating the workload with respect to the planned working hours. Meaning the current activity is finished even if working time is over. Results show, on the one hand, that the best output in terms of finished orders for anatomical models is the double resource scenario 2_3 due to their long printing time. On the other hand the three shift scenario gives the best output for implants. This can be explained by the fact that the average printing time of implants is lower and therefore the printer can be higher utilized in three shifts. With respect to anatomical models three shifts without more printer-resources don't increase the performance. In all scenarios the radiology technologists is the bottleneck. This can be explained due to the high segmenting and modeling activity duration. Implants, with less resource intense manufacturing, are generally processed faster. Moreover, this scenario shows that the workload of printers can only be raised with more staff available. With respect to limited resources, adding one radiology technologists and one low temperature printer and operating with two shifts would give the best performance. This scenario is evaluated in the additionally added scenario 2_7, which shows superior throughput times with just using little more resources.

6.3 Demand Growth Scenarios

The results of the scenarios 3_1 and 3_2 show that due to increasing demand the workloads are 2-8% higher. Compared to the one-year baseline scenario the effect of the learning curve can be seen in the minimum throughput time of 1,61 days for anatomical models and implants. As a result of the increasing demand the average and median throughput times are longer. A significant increase of the throughput times is noticeable after three years. From this we infer that the demand at this point is the margin demand for the baseline scenario resources to fulfill the process efficiently. At that point in time we recommend adding resources to maintain the performance level of the medical 3D printing center of the first three years. Furthermore in the long run the allocation of the working times referred to the main processes explained in section 4.1 can be determined. Manufacturing duration of anatomical models is predominantly defined by the printing time, which is 72% of the overall working time. For implants the sterilization requires with 45% most of the time. As a result of the lower weight printing is here just 34% of the overall working time.

6.4 Specific Evaluation Scenarios

Scenarios 4_1 and 4_2 consider the goal of the CAMed project to print implants close to (a day before) or even during surgery. Significant time reductions are required and can be reached with enhanced printing technologies (faster printing) and with avoiding the need for additional sterilization e.g. by already producing a sterile product. Moreover, the automation of segmenting and modeling activities, with computer-aided software, is crucial for a short throughput time. Comparing to the baseline scenario, setup 4_1 brings already a significant step towards the goal of 4 hours throughput time. Nevertheless the target is only reached in the best case, see min. throughput time in table 4. To meet the target of 4 hours throughput time in average our results suggest that the duration of order processing activities has to be shortened too.

7 CONCLUSION, LIMITATIONS, AND OUTLOOK

This paper presents the application of modeling and simulation in health care for the purpose of early stage strategic decision making for the design of a medical 3D printing center at point of care. A scalable simulation model was implemented and a scenario-based approach was applied to estimate the potential for a daily clinical use. The results indicate potential operations performance and required resources for a given demand. Various allocations of resources were evaluated to understand their potential impact on the operations performance and to identify the levers for performance improvement. The effects of a learning curve and a growing demand over time were also evaluated. In the demand growth scenarios it was shown at what point of time it may be required to invest in additional resources to maintain the performance of the medical 3D printing center. Additionally in the specific evaluation scenario it was shown that the simulation model can also give indications for required technological enhancements and process improvements to achieve certain targets. These results also indicate that, despite the early stage of the business and the initially data-poor environment, the simulation model can serve as tool that supports the rough sizing of a medical 3D printing center. Furthermore, a successful application of the HCCM framework and the corresponding HCDESLib has been shown.

Due to the early stage of the 3D printing research lab and the initially data-poor environment the simulation model may not be complete and the data may not be accurate. At this point of time it was not possible to validate the outputs of the simulation model with the real world, as the medical 3D printing center for daily clinical use doesn't exist yet.

The simulation model should act as base for further enhancements concerning the model and the ongoing process of gaining more data from the real world. It should further support the activity of establishing a medical 3D printing center at the hospital. It is planned to use the generated operational data for a quantitative business case analysis to support the decision regarding the economic feasibility for daily clinic operations. Further potential research activities are to integrate aspects of production planning and aspects of synchronizing operation planning with the production process into the simulation model.

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