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THE USE OF SIMULATION MODELS FOR ANALYZING COSTS IN ADDITIVE MANUFACTURING FACILITIES

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Abstract: *In the current market environment, characterized by volatility and uncertainty, informed decision-making is crucial for the sustainability and success of entrepreneurial and business ventures. This paper explores the practical application of simulation models as analytical tools, demonstrated through the creation and analysis of a simulation model of an additive manufacturing facility. Simulation models are effective tools for gaining a deeper understanding of real-world systems. Additive manufacturing, as a sustainable alternative to traditional methods, is gaining traction, with fused deposition modeling being particularly notable for its safety, widespread adoption, and cost-effectiveness. By simulating a small to medium-scale manufacturing operation, this paper aims to provide practical insights into the integration of simulation models and small-scale manufacturing facilities that implement additive manufacturing methods. These insights are designed to assist decision-makers in making informed decisions, weighing alternatives, and mitigating unnecessary waste and risk when initiating an entrepreneurial venture.*

Keywords: *Sustainable management, Simulation models, Additive manufacturing*

1. INTRODUCTION

The turbulent and dynamic state of today's market requires modern management to, for the most part, make informed decisions whilst tackling growing uncertainty. The quality of informed decisions will directly affect the health, longevity, and sustainability of entrepreneurial ventures and long-standing organizations. The uncertain market state makes educating new and up-and-coming personnel in using simulation analysis tools paramount. Simulation models, created using simulation analysis computer programs, play a crucial role in combating market uncertainty by allowing users to replicate observed real-world systems and experiment within those systems in an environment of massively reduced risk. Parallel to the increasing market uncertainty, an old challenge comes to light – the need for more responsible, sustainable, and just-in-time production. As we move forward in today's hyper-productive era, our effects on the environment become ever-present. As new challenges emerge, so do new manufacturing techniques in the form of additive manufacturing methods.

This paper is dedicated to exploring the potential of integrating simulation models and additive manufacturing techniques. To illustrate this, we present a simulation model of a small-to-medium-scale manufacturing operation using readily available additive manufacturing technology. Our aim is to provide a practical demonstration of how simulation models can be effectively used in the context of additive manufacturing, thereby offering valuable insights for decision-makers in small-scale manufacturing ventures.

2. ADDITIVE MANUFACTURING

Additive manufacturing refers to one of three categories of manufacturing methods: formative, subtractive, and additive manufacturing. Formative manufacturing methods create desired geometric shapes by using molds and raw materials (usually in a liquid state) capable of conforming to the shape of the cavity created by the mold. Subtractive manufacturing methods create desired geometric shapes by intentionally removing material from a raw piece of chosen material. With the advent of CNC (computer numerically controlled) lathes in the '50s at MIT (Massachusetts Institute of Technology), highly precise, repeatable, and predictable CNC subtractive manufacturing became possible(Smid, 2003; Xu, 2009). AM (Additive Manufacturing) methods create desired geometric shapes by applying successive layers of raw material, building the desired shape up layer by layer (Wong & Hernandez, 2012). Contemporary AM methods use CNC technology to control machines equipped with tools that implement an array of manufacturing technologies. Notable additive manufacturing methods include SLA (stereolithography), SLS (selective laser sintering), and FDM (fused deposition modeling) (Danut Mazurchevici et al., 2020). For the purposes of this paper, our focus was on additive manufacture by FDM, as FDM has reduced health risks in comparison to SLA, a smaller barrier of entry compared to SLS and overall higher adoption rate and user support in comparison to both SLA and SLS (Chan et al., 2020; Danut Mazurchevici et al., 2020; Huang et al., 2020). Manufacturing using FDM can be performed by following this process (Jumaah et al., 2018):

1. Creating a 3D model of the desired shape using CAD (Computer Aided Design) software,
2. Creating a *.stl* file from the created 3D model,
3. Slicing, or creating a series of commands for the CNC machine to execute (*.gcode* file containing toolpaths and other miscellaneous commands) using slicing software,
4. Configuring machines and importing the *.gcode* file,
5. Surveilling the execution of the commands in the *.gcode* file,
6. Removing, processing, packing the finished units, and preparing the machine for future use.

Advantages of FDM include the use of stable and safe to handle raw materials, simple post-processing operations, low barrier of entry, serviceable and upgradable machinery, the ability to produce highly complex geometries as well as embedded components, scalability (both quantity and size) and just-in-time production (Antic et al., 2023; Danut Mazurchevici et al., 2020). Disadvantages of FDM include low manufacturing speeds for complex geometries, embedded failure points due to layered construction, structural compromises (for parts with less than 100% infill), complications when designing overhangs, surface roughness and exposure to VOC's (Volatile organic compounds) (dependent on chosen material) while machines are in operation (Chan et al., 2020; Li et al., 2017). All three manufacturing methods produce some amount of scrap material. However, scraps created by FDM serve as structural supports for overhangs or supports for better adhesion to the build plate and can be recycled for future use. Parts meant to be manufactured can be designed around these constraints in such a way as to eliminate or at least minimize the amount of necessary support material, which would later become scrap (Paris et al., 2016).

2. MODELING REAL-WORLD SYSTEMS

Modeling serves as a method for comprehending and learning from and about real-world systems, which consist of any number of interdependent elements whose interactions influence their changes and observed outcomes of the system as a whole (Radenković et al., 2009). Models are constructed by observing such systems, identifying elements impacting outcomes, and specifying their relationships, attributes, and rules to replicate reference outcomes. The level of detail in a model is determined by abstraction, a process where the relevance to an outcome of specific details is determined (Grigoryev, 2022). Models can be physical or conceptual, depending on the tangibility of the system. Physical models represent tangible objects, while conceptual models illustrate relationships between intangible concepts. This paper focuses on simulation models, which enable users to simulate real-world systems in a risk-free environment, providing control over attributes and, in some cases, passage of time (Борщев Андрей, 2013). Simulation models are crucial for decision-making when real-world experimentation is costly or impractical. They can be digital and depict physical or conceptual systems. For example, Computational Fluid Dynamics (CFD) models can simulate aerodynamics, while conceptual simulation models can depict logistics, product adoption, organizations, or environmental impacts (Grigoryev, 2022). Digital simulation models offer advantages such as a digital environment, control over resources and time, scalability, and dynamic system representation. Simulation models are executable and require running in order to conduct experiments. Each run provides feedback based on parameters, variables, dependencies, and rules. Modelers can adjust details and inputs for comparison. Three distinct methodologies, System dynamics modeling, Agent-based modeling, and Discrete event modeling, are used to build simulation models, chosen based on the required level of abstraction for a faithful representation of the observed system. In this paper, agent-based modeling combined with discrete event modeling was employed to simulate a 3D printing workshop.

3. MODELING A 3D PRINTING WORKSHOP

To create a simulation model, it is necessary to describe the system being modeled as well as choose the appropriate software to use. In our research, a model of a 3D printing workshop has been created to analyze which combinations of salary, number of machines, number of employees, level of margin, and price per spool of material are optimal for which printer. The simulation model of a 3D printing workshop has been created using the AnyLogic software, utilizing the Analysis, Controls, Agent, and Process Modeling libraries (Grigoryev, 2022). The created simulation model offers visualizations of an income statement, expense structure, the distribution of prices per unit per project, and the distribution of time spent on various activities during the manufacturing process over the course of three simulated years. The model consists of the following agents: Main, Project, Worker, and Printer.

3.1. Agents Worker and Printer

The Worker and Printer agents define two inexhaustible resources that make manufacturing possible. The worker agent is defined by their speed, set at two meters per second. The printer agent is defined by the following parameters listed in Table 1 (*Bambu Lab A1*, 2023; *Original Prusa XL Semi-Assembled Single-Toolhead 3D Printer*, 2023).

Table 1: Parameters defining the Printer agent

Parameters	Unit of measurement	Data type	Short description
BuildX	mm	double	Build plate size of a specified printer in the X-axis
BuildY	mm	double	Build plate size of a specified printer in the Y-axis
BuildZ	mm	double	Build plate size of a specified printer in the Z-axis
PrintSpeed	mm^3/min	double	Volumetric flow rate
PrintArea	mm^2	double	Area within which a printer can print
PrintVolume	mm^3	double	Space in which a printer can print
ElConsumption	kWh	double	Electric consumption of a printer during operation

3.2. Agent Project

Projects are defined by a population of Project agents. The Project agent represents the projects requested by clients. Several parameters and variables define the Project agents. Some variables refer to common attributes found in publicly available *.stl* files (*Printables*, 2023), while others refer to derived attributes necessary for multiple calculations regarding cost and manufacturing time (Ellis, 2023). The variables and parameters defining projects are listed in Table 2.

Table 2: Project agent parameters and variables

Type	Name	Unit of measurement	Short description
Parameter	wc	mm	Thickness of a unit's shell.
Parameter	Infill	%	Percentage of unit's infill.
Variable	x	mm	Size of unit in the x-axis.
Variable	y	mm	Size of unit in the y-axis.
Variable	z	mm	Size of unit in the z-axis.
Variable	q	q	Quantity of requested units.
Variable	Areaq	mm^2	Area of a unit on the build plate.
Variable	Shellq	mm^3/q	Volume of a unit's shell.
Variable	Infillq	mm^3/q	Volume of a unit's infill.
Variable	VolumeMat	mm^3/q	Volume of material per unit.
Variable	VolumePiece	mm^3/q	Volume taken up by a unit.
Variable	VolumeProject	mm^3	Volume of material spent for all units of the project.
Variable	AreaProject	mm^2	Area taken up by all units of the project.
Variable	Box1,Box2,Box3Count	box	Number of boxes used for the project.
Variable	PackMaterial	mm^3	Volume of packing material used for the project.
Variable	MachineCount	machine/s	Number machines required for the project.
Variable	MatProject	mm^3	Material used for the project.
Variable	TimeProject	h	Time spent on project.
Variable	Work Software, ConfigPostPack, Time	min	Time spent on individual activities.
Variable	Material,Electric,Box,PackMaterial,Worker Cost	RSD	Associated costs of materials and activities.
Variable	CostProject	RSD	Cost of entire project.
Variable	ValueOfProject	RSD	Market value of the project.
Variable	PricePerUnit	RSD/q	Price per unit of the project.

3.3. Agent Main

The agent Main, serving as the work surface, contains several parameters defining the dimensions of the packing boxes best suited for a chosen printer, the salary for the workers as well as their hourly rate. Aside from these parameters, Main contains several parameters defining the minimum and maximum size of the units requested in projects, number of boxes, amount of packing material, amount of filament, number of spools used during the simulation run, as well as elements of the simulated income statement. Main also contains the visualizations mentioned above and controls for choosing which printers, paygrade, percent of margin, and cost of material are to be simulated. Most importantly, Main contains the modeled process flow of production and packaging using FDM, which has been built using elements from Anylogic's Process Modeling Library (Figure 1).

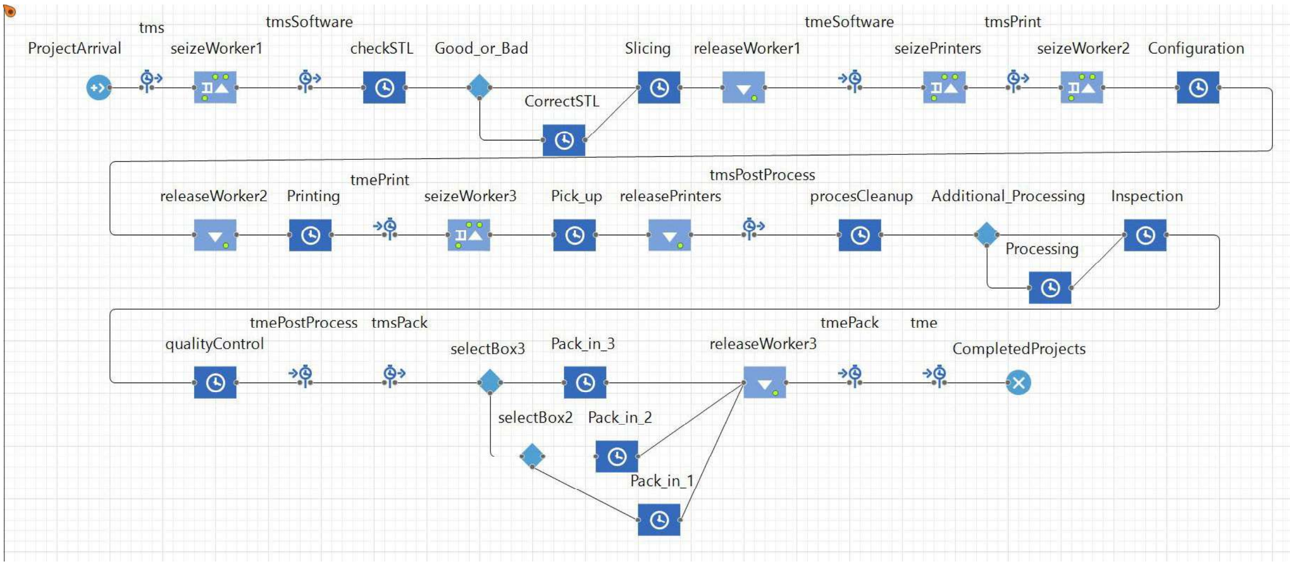

Figure 1: Process flow of a 3D print shop

4. SIMULATION EXPERIMENTS

Upon running the simulation, the user is prompted to choose a desired number of machines and workers, salary for the workers, percentage of margin, price of a spool of material, and type of printer they want to simulate. Each run is limited to 3 years of simulated time.

Projects upon arrival have their x, y, and z values determined via triangular distribution bounded by the minimum and maximum allowable values defined upon choosing a printer type (the minimum values are always 10mm, and maximum values are defined by subtracting 10mm off from the dimensions of a printers build area). A uniform discrete distribution bound between 1 and 20 defines the number of requested units. The volume of a unit is defined as a product of the *x*, *y,* and *z* values. After the project has arrived, a worker is seized. The worker examines whether the attached *.stl* file is suitable for FDM manufacturing. If the file is suitable for printing, it is forwarded; if not (which has been defined as the case for 10% of arrivals), it is corrected by the worker. After the examination/correction process, the worker will take the *.stl* file and process it using slicing software (such as Cura, Prusa slicer, Orca slicer, etc.). During this process, several attributes listed in Table 3 are calculated.

Table 3: Attributes calculated during the slicing process

attributes	Unit	Description
Shellq	mm^3/unit	Sum of volumes of individual sides, where *wc* is the height of the cubes.
Infillq	mm^3/unit	Product of the infill percentage and difference between the unit's volume and their shell.
VolumeMat	mm^3/unit	Sum of the shell and infill volumes
VolumeProject	mm^3	Product of *q* and the material necessary for a single unit (VolumeMat)
Areaq	mm^2/unit	Product of *x* and *y*
AreaProject	mm^2	Product of the area of a single unit (Areaq) and *q*
MachineCount	units	Ceiling of the quotient of the AreaProject value and the area of build plate

Once the file is sliced and the *.gcode* is generated, the worker will seize the necessary number of printers and configure them for the current project. The printers are now ready for manufacturing. During this step, the amount of material spent on the project is calculated, as well as the time needed to manufacture the requested units as a quotient of the volume of material to be printed and the chosen machine's volumetric flow rate (the volume of material, the machine is able to extrude per unit of time). After printing, a worker retrieves the finished pieces from the printer/s, a process during which the costs of material and electric power spent for the project are calculated.

Material and electrical costs associated with that specific project are tallied up with the costs of other projects during the run, forming TmaterialCost and TElecCost. Upon releasing the printers used for the project, the number of spools spent during the simulation is calculated, as well as the time spent printing that specific project. Following the printing process, a worker assesses whether additional processing is required (it is simulated to be necessary for only 10% of arrivals). The project is then processed (if necessary) and inspected by checking whether the shape of the resulting units complies with the attached digital model file. Post inspection, a worker conducts a quality control check, during which units are checked for defects or faults, after which packing can commence. The box size to be used is determined by checking multiple conditions. These conditions effectively check whether the units can fit in a specific box size in any orientation. During the packaging process, the number of boxes used is recorded as well as the amount of packaging material used (as the product of q and the difference between the volume of a box and the volume of a unit) and the cost of the boxes spent on packaging the finished units of the project is calculated.

After packaging, costs related to labor and packing materials put into the project are calculated, and following this, the total costs of the project. Upon releasing the worker, the project is considered complete, and the entire project's value is calculated by multiplying the entire project's cost by the selected margin. After calculating the price for that specific project, the simulated balance sheet elements are calculated by calculating fixed and variable costs, total costs, and marginal and simulated profit. Simulation runs will pause at the break−even point (if applicable). This pause, if the break-even point is achieved, can offer the user information on when the break-even point could be achieved in the real world, or after how many completed projects, as well as all the other indicators in Figure 2, such as the average manufacturing time or average price per unit.

Figure 2: Break-even point for 9 Ender3 printers, where workers are paid the Median salary, margins are at 50% and the material used costs 2600 RSD/spool.

4.1. Possible application

The results gathered from the simulation experiments can assist the users in determining which scenario would best suit their means. In other words, a simulation experiment can give them a glimpse of what's to come if they were to pursue an specific combination of attributes. An example of which is given in Table 4.

Table 4: Simulated Profits across all combinations of workers and printers, where the margin is at 25%, the workers are paid a median salary, and the cost per spool is 2400 for the Creality K1 machine/s

Profit [RSD]	3	6	9
1	3,088,785.26	2,923,987.71	2,300,800.10
2	430,741.15	-70,790.59	-1,087,969.75
3	-2,704,360.34	-4,046,217.61	-3,445,197.36

Table 5 shows that employing more than two workers is unprofitable. Furthermore, profitable combinations given in Table 4 have different break/even points, as demonstrated.

Table 5: Break-even points of all profitable combinations of the K1 printer with 25% margins and material priced at 2400 RSD/spool

Number of workers	Number of machines	Profit	Break/even point is achieved after
1	3 machines	3,088,785.26	57 days
1	6 machines	2,923,987.71	112 days
1	9 machines	2,300,800.10	286 days
2	3 machines	430,741.15	263 days

5. CONCLUSION

Today's uncertainty, paired with a global need for sustainable production methods, poses a new and complex challenge, necessitating a novel approach to production and analysis. This paper emphasizes the importance of informed decision-making in a sustainability-oriented market by showcasing a simulation model built to focus on the manufacturing cost analysis of a 3D printing workshop. By utilizing Anylogic's Process Modeling Library, it has become possible to increase the accuracy of entrepreneurs' and managers' predictions when making decisions regarding the acquisition of different means of production, the structure of costs, the necessary time to achieve the break-even point, etc. Through simulation experiments, decision-makers can assess not only the potential outcomes of their chosen strategies but also what to expect until they reach their desired outcomes. This can offer decision-makers a competitive advantage while budgeting and a sustainability advantage when considering the fact that the resources used in simulation models are fictitious.

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