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Simulation Game Concept For AI-Enhanced Teaching Of Advanced Value Stream Analysis And Design

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Abstract

Value stream analysis and design is employed globally by improvement teams within industrial settings to maximize value creation and eliminate waste. For ending methodical time-centricity, research expanded the methodology to incorporate diverse facets like material flow cost accounting, information logistics, and external influence factors. These enhancements, along with increasing data volumes, are prompting a re-evaluation of how professional improvement teams should think and operate. Consequently, a transformation of the pedagogical approach used for educating students and professionals necessitates novel solutions. Conventional teaching methods such as expository lectures are widely considered inadequate in promoting knowledge retention and engagement. So far, existing research has not yet resulted in a solution that can effectively impart the methodological complexity of advanced value stream analysis and design in a motivating and vivid fashion. To address this gap, this paper applies a tailored CRISP gamification framework to develop a simulation game concept. These concept enables AI-enhanced teaching of advanced value stream analysis and design focusing on identification of multi-stage resource-efficient optimization strategies. Through integration of game-based learning with AI a trained reinforcement learning agent can act either competitively or cooperatively, creating a unique form of teaching accounting the aspects personalization, adaptive feedback, content creation, and analysis and assessment.

Keywords

Advanced Value Stream Analysis and Design; CRISP Gamification Framework; Simulation Game; Artificial Intelligence; Game-based Learning; Resource-efficient Thinking

1. Introduction

By advancing the methodology of value stream analysis and design—a concept originating from lean management—to embrace aspects such as material flow cost accounting [1], information logistics [2], and the integration of external influencing factors [3] novel opportunities as well as challenges emerge. Major aspects such as material and energy-based waste, digitalization, but also the sales market, labour market, procurement market, and other external aspects like policy and trends can be included in analysis and design through advanced key performance indicators, thus enabling holistic optimizations.

Arising diversity within the methodology consequences an aggregate growth in application complexity and available data volumes, which changes how improvement teams should think and operate in industrial setting. Thus, also educational training of students and professionals must adapt, necessitating the development of novel solutions. It is broadly acknowledged that conventional pedagogical methods, like e.g., expository lectures, lack efficiency regarding knowledge retention and engagement. A minority of researchers expresses scepticism that gamified learning effects can be transferred to non-game contexts

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through the process of gamification [4, 5]. Meta-analyses have proven that gamification in formal education yields significant positive effects on cognitive, motivational, and behavioural aspects of learning [6, 7].

Current research has applied gamification to cultivate understanding of several facets of lean management [8, 9, 10]. These efforts have not yet yielded an approach that successfully encapsulates and conveys the methodology of advanced value stream analysis and design in a motivating and vivid fashion. To fill the identified gap, this paper employs a tailored six-step CRISP gamification framework. The resulting simulation game concept encourages players to develop multi-stage resource-efficient strategies reinforcing sustainable thinking. Enhancing the simulation game concept by game-based learning with AI enables the integration of an agent trained via reinforcement learning. Its deployment can be either competitively or cooperatively, creating a unique form of teaching accounting personalization, adaptive feedback, content creation, and analysis and assessment.

This paper initially introduces the theoretical background of the simulation game. Next, the six-step CRISP gamification framework is applied while the substance focuses on results, i.e., game preparation and game modelling. Detailed derivation and explanation of the CRISP gamification framework will be part of an individual publication currently in preparation. Lastly, conclusion and an outlook on further research is presented.

2. Theoretical Background

2.1 Advance Value Stream Analysis and Design

Within application of value stream analysis and design initially an improvement team maps the current value stream of a relevant product family and illustrates it utilizing standardized value stream elements (value stream analysis) [11]. Subsequently, wastes are identified applying the concepts of "muda", "mura", and "muri" [12]. By eliminating identified wastes and applying value stream design guidelines the improvement team designs a target value stream which is optimized in terms of lead time (value stream design) [11, 13]. Ubiquitously guiding within all activities is the ideal state known from the toyota production system, also referred to as the "north star", consisting of 0 defects, 100 % value creation, one piece flow to customer demand and safety for people [14].

By research, the methodology of value stream analysis and design is advanced by diversifying input and output features [15, 16, 17]. Within this paper, the concept of advanced value stream analysis and design refers exclusively to the advancements by material flow cost accounting [1], information logistics [2] and the consideration of external influencing factors [3]. Figure 1 exemplifies a current value stream of this advanced form of value stream analysis and demonstrates the methodological complexity that is to be conveyed via the simulation game concept to be developed.

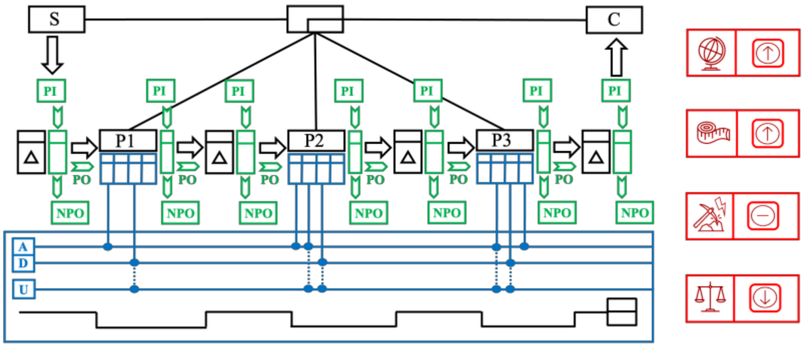

Figure 1: Exemplary Illustration of a Current Value Stream Utilizing Advanced Value Stream Analysis

Lead time centered elements of the conventional value stream analysis including suppliers (S), processes (P), inventories, customers (C), and the lead time ladder are illustrated in black. For resolving the fact of incomplete improvements solely favouring the lead time, the consideration of material and energetic wastes such as excessive energy consumption or material waste is made available via material flow cost accounting according to DIN EN ISO 14051:2011 [18]. Illustrated in green, input and output of a process is differentiated into product input (PI), product output (PO), and non-product output (NPO). The costs of product input, product output and non-product output are structured via material costs, energy costs, system costs, and waste management costs. Additionally, key performance indicators like absolute monetary value creation, relative monetary value creation, and degree of value creation can be used for representation [1].

The integration of information logistics facilitates tracking of activities and key performance indicators information flow via analog (A) and digital storage media (D) and their utilization (U), illustrated in blue. Evaluation can be based on the key performance indicators digitization rate, data availability, and data usage. Especially media discontinuities between the storage media become visible and thus enabling the initiation of selective optimization projects in the context of digitization [2].

Value stream analysis and design primarily according to internal factors may not always be effective. For example, if the geopolitical situation of crucial suppliers is critical coupled with long supply chains, a lack of material availability can quickly lead to costly production restrictions. Therefore, external influencing factors, illustrated in red, derived from sales market, labour market, procurement market, and other external factors such as politics, social area, technology, and general trends should be included to empower holistic optimization [3].

2.2 Gamification Frameworks

Through applying gamification frameworks to lean management tools, like advanced value stream analysis and design, efficiency can be improved in lean initiatives while raising employee engagement. Cross-linking can enable benefits as e.g., boosting enthusiasm, encouraging collaboration, and promoting creativity [19].

Games are voluntarily engaging and formally organised activities with objectives and rules, which might be physical or mental, and can be used to lead players into competition, education, or entertainment. Simulated environments are used to experiment with systems in simulation games, a specific category of game that can be used to teach [20]. Gamification is the process of incorporating game mechanics and strategies into non-game environments to engage and encourage players. To increase interest and participation, it utilizes scoring systems, leaderboards, and awards [21, 22]. Interactive digital or analog games with educational or informational objectives are referred to as serious games which are fostering social connection, transmit knowledge, or train skills [23]. Using specifically created games knowledge is imparted and skills are developed incorporating game elements with educational material [24].

For designing games, various frameworks and models exist, such as the six steps to gamification [25], the mechanics-dynamics-aesthetics (MDA) framework [26], and the octalysis gamification framework [27]. Beyond that, principles unrelated to gamification, such as design thinking, can be used within the creativity processes of game development [28]. Distinct gamification frameworks and models are frequently combined to create unique solutions for specific tasks. Combining gamification principles with software development models, for example, can help to depict complex processes in a game while promoting player participation [29]. Overall, gamification frameworks can provide a foundation for the development of games and gamified applications. In context of lean management tools like advanced value stream analysis and design, there is a necessity for an updated and comprehensive solutions that embrace the core idea of gamification while representing complex methodologies.

2.3 Game-based Learning with Artificial Intelligence

Game-based learning with AI can be applied in the context of lean management to enhance training, problem-solving, and decision-making in organizations within activities related to lean six sigma, kaizen, manufacturing, leadership, and inventory management [19, 30].

Artificial intelligence (AI) game-based learning is an educational technique that combines AI technology with interactive games to enhance the overall learning process. Giving users an intense and individualized learning experience, this method blends fun and motivational aspects of games with intelligence and adaptability of AI. Objective is to encourage engagement, problem solving, critical thinking, and knowledge retention to make learning more enjoyable and effective [31]. Core elements of game-based learning with AI are personalization, adaptive feedback, content creation, and analysis and assessment [32]. AI algorithms stay astute during gameplay, providing players with real-time feedback when they encounter obstacles or make mistakes. These timely cues, ideas, or explanations from the AI act as guiding beacons, directing learners to the appropriate solutions. Embracing a growth mindset, adaptive feedback fosters an environment that encourages continuous improvement of the player [33].

AI can enable develop dynamic and diverse gaming content, continually generating new levels, challenges, or scenarios. Such adaptability aids in preventing boredom and successfully retaining players attention and motivation throughout their educational experience [34]. AI-driven analytics play a vital role in monitoring users progress, effectively pinpointing areas of strength and weakness. Armed with data, educators and developers gain invaluable insights into learners performance, allowing them to refine the learning content and overall experience, thereby fostering continuous enhancement [35]. In essence, the integration of AI and game-based learning transforms the educational environment by making the process appealing, dynamic, and customized to player's needs. Fusion of gaming features and artificial intelligence in this instructional technique not only enthralls but also empowers students, reigniting their enthusiasm for academic advancement and knowledge acquisition.

2.4 Related Work

In existing research, few efforts been made to leverage presented frameworks and models to develop full-fledged simulation games in the context of advanced value stream analysis and design. Different approaches were followed to generally gamify different lean management tools such as shopfloor management [8], the SMED method [9], or the 5S method [10], or to simply model and simulate the process of value stream analysis [36, 37, 38]. In scope of advanced value stream analysis and design, there is limited application of gamification frameworks. Existing solutions are outdated and do not fully consider the methodological requirements and the core idea of gamification, namely, to generate engagement and motivation, while at the same time adequately representing the complex methodology of advanced value stream analysis and design. Therefore, there is a need for innovative approaches to effectively develop games in this context.

3. Methodology

Objective of this paper is to develop a concept for a computer-based simulation game. This simulation game aims to convey the complex methodology of advanced value stream analysis and design to students and professionals in cooperation and competition with an artificial intelligence (AI) in a motivating and vivid fashion – thus departing from inefficient expository lectures.

In accordance with the lean start-up philosophy and the concept of the minimum viable product [39], the simulation game of this paper should be conceptualized in a cost-efficient and agile manner. To realize this objective, this paper adapts a new six-step CRISP gamification framework, which is illustrated in Figure 2. This tailored procedure model results from merging the six steps to gamification by Werbach and Hunter [25] and the CRISP-DM model by Wirth and Hipp [40]. Contrasting other widespread gamification frameworks such as mechanics-dynamics-aesthetics (MDA) [26] or octalysis [27], this novel model offers a cyclical IT-oriented approach that provides a continuous development flow from conceptual design to the digital realization of a computer-based simulation game. The derivation and detailed explanation of this framework will be part of a separate publication currently in preparation. The CRISP-DM approach is applied in big data and data science, developing solutions that deal with large data sets and probabilities – aspects that also occurs in simulation games. Especially suitability of the new framework and its transfer to the new domain needs to be investigated and discussed in detail.

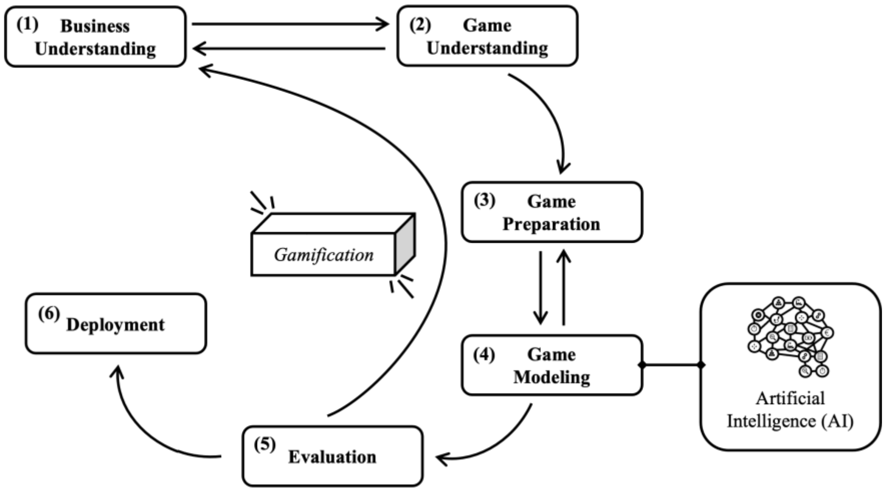

Figure 2: Six-Step CRISP Gamification Framework

The application of the six-step CRISP gamification framework starts with business understanding (1), in which the business context is described and immediate business goal of the system to be gamified is defined, checked for relevance, and evaluated. In subsequent game understanding (2), the target behaviour within the game is specified in bi-directional alignment with the business understanding as well as the player target group is characterized. During game preparation (3), the fundamental framework of the game is conceptualized utilizing the concepts of activity cycles and progression stairs. This preparation is subsequently used in game modelling (4) via creativity processes with appropriate tools to model the simulation game with AI. Lastly, the developed game is logically checked, tested, validated, and compared with the defined business objective in the context of evaluation (5). If the game meets the business objective, it can be deployed (6), if not, the game development is continued iteratively.

4. Implementation and Results

To understand the business context as part of business understanding, the explanations presented in section two on theoretical background should be viewed as foundation of the simulation game. Thereby, overall objective of the game is to enable vivid and motivating teaching of methodological knowledge with AI while explicitly encouraging the development of multi-stage resource-efficient strategies and sustainable thinking.

The target behavior of a player within the simulation game associated with game understanding involves application of traditional and advanced value stream design guidelines to design and model optimized target value streams towards the "north star" – including understanding the implications across a variety of scenarios while strategically deploying resources. It is crucial that the target player group, consisting of lean management affine male and female students and professionals, not solely understand the method, but can understand the real-world complexity and are able to implement the concept over the long-term achieving superior improvements in competition with AI [41].

4.1 Game Preparation

After clarifying the simulation game objective, player target behavior and player characterization, the simulation game can be generally conceptualized within game preparation. Following Figure 3 illustrates the simulation game concept by applying concepts of progression staircase and activity cycle [25] on the theoretical background of advanced value stream analysis and design. The simulation game concept aims to teach advanced value stream analysis and design in a gamified context and to reinforce resource-efficient thinking. The progression stairs of the game's graphical user interface (GUI) show players progress through a total of five game turns, which are also highlighted on the turn pointer, within which players start at the starting point and compete to reach the target point "north star". The five-step activity cycle (step 0 to step 5) runs turn-based and allows players to choose from random sets of actions in each round, resulting in positive or negative feedback from the payout generator. After five turns, the player who manages resources most efficiently and gets closest to the "north star" wins.

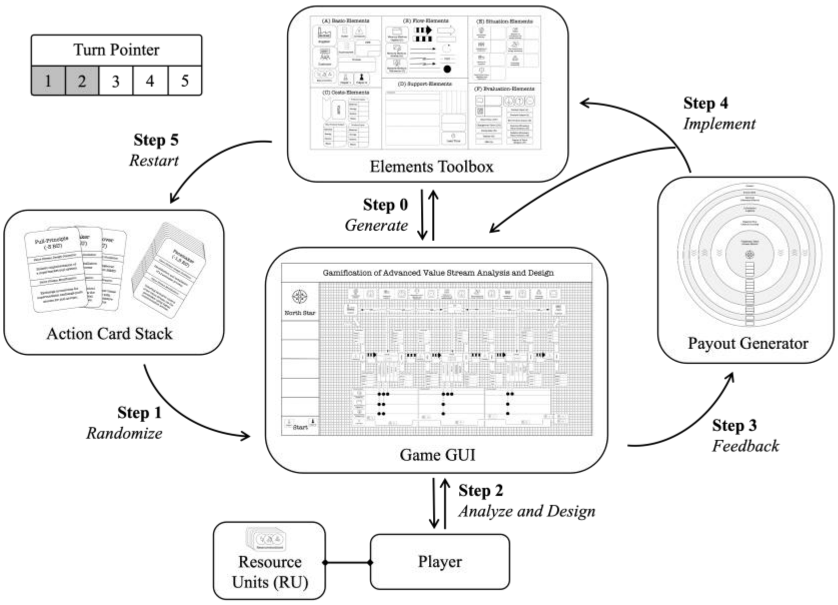

Figure 3: Five-Step Simulation Game Concept Including Progression Stairs and Activity Cycle

Game setup initiation is executed via the computer-based generation of a value stream, as analysis and design object, at the game GUI using preparate value stream elements from the elements toolbox and value stream patterns. Player's game figure starts at the starting point on the progression stairs of the game GUI, and each player receives a defined amount of resource units (RU) (e.g 10 pieces) to be invested for advanced value stream design during the five turns of the simulation game. After the action card stack (e.g. 25 pieces) is shuffled and a defined number of cards (e.g. 5 pieces) is randomly distributed to each player. The action cards represent traditional and advanced value stream design guidelines including name, resource costs for activation, description, and modification instructions. Players generally are keeping their cards secret from each other, creating elements of uncertainty and competition.

Subsequently, within analysis and design players strategically choose based on the made-up value stream at the game GUI and their available cards which action card to activate and place it face up. Each player can only activate one card per turn and must pay the resource unit cost for its activation. In accordance with the combination of the value stream pattern and the played action cards, the payout generator determines the players individual reward via similarities in underlying complex graph networks. The player with highest turn-reward wins the current game turn and can advance one step closer to the "north star" on the progression stairs of the game GUI. The value stream design guideline associated with the turn-winning player's card is implemented into the existing value stream using modification information from the action card and value stream elements from the elements toolbox.

At the turns end all remaining action cards are collected and shuffled for the next turn. The game proceeds for five consecutive turns, allowing players to make resource-efficient decisions over long term to achieve outstanding multilevel improvements in a competitive environment. The objective of the simulation game goes beyond maximizing rewards in a single round; it emphasizes strategic resource management to achieve long-term success and come closest to the "north star". This game-based learning concept encourages players to make well thought-out decisions and fosters continuous learning and improvement.

4.2 Game Modelling and AI Integration

While preparation reveals functionality of the simulation game concept, modeling how the simulation game can be played in competition or in collaboration with an AI to enable self-learning follows. It is well known that AI-based robots have already beaten grandmasters in the games such as "chess" and "go" [42]. Recent developments allow today not only to reach but to exceed human expert-level performance even in complex games like "stratego" with 10^{535} possible states [43]. To achieve such a performance, but also to enable training with and against AI-based robots, different types of reinforcement learning (RL), i.e., model-free multiagent reinforcement learning, can be utilized.

Reinforcement learning enables an agent to learn how to maximize rewards in the future by experiencing rewards and punishments. As basis for application, the agent-environment interface required for the RL model consists of the five key components: agent, actions, environment, rewards, states, and policy [44]. Figure 4 illustrates how the five key components are integrated into the simulation game concept, enabling the training of an agent. Training of the agent's neural network follows the game process and progression. From the action card stack, which reflects various optimization measures, randomly five cards are assigned to the agent. These represent the actions for this turn and activate the neurons. Within the environment, consisting of game GUI and elements toolbox, the present value stream on the game GUI is transformed into a value stream graph with nodes and edges according to graph theory. Referring to this value stream graph (value stream pattern), the agent selects one of its actions and activates it. The agent receives feedback via the reward function of the payout generator. The payout generator is embodied by a complex value stream graph network consisting of value stream pattern variations in combination with actions and corresponding rewards. Through a similarity analysis within the complex value stream graph network versus the present value stream graph and the activated action, the reward can be determined and transferred to the agent. Using the value stream modification information associated with the action, optimization action can be implemented into the environment, resulting in a new state for the next game turn. The overall agent's policy results from the already described game objective, target behavior, and the five-round game process and specifies the rules according to which the agent acts and learns. Alongside the rules and regulations, comprehensibility and fairness are key factors of the policy. The agent implemented in the simulation game concept can be deployed not only primarily as an opponent or duplicated as multiple opponents to facilitate learning. Secondarily, it can also be integrated as an ally in the learning process. The application mode and level of difficulty can be further customized, thus enabling a novel form of teaching featuring personalization, adaptive feedback, content creation, and analysis and assessment.

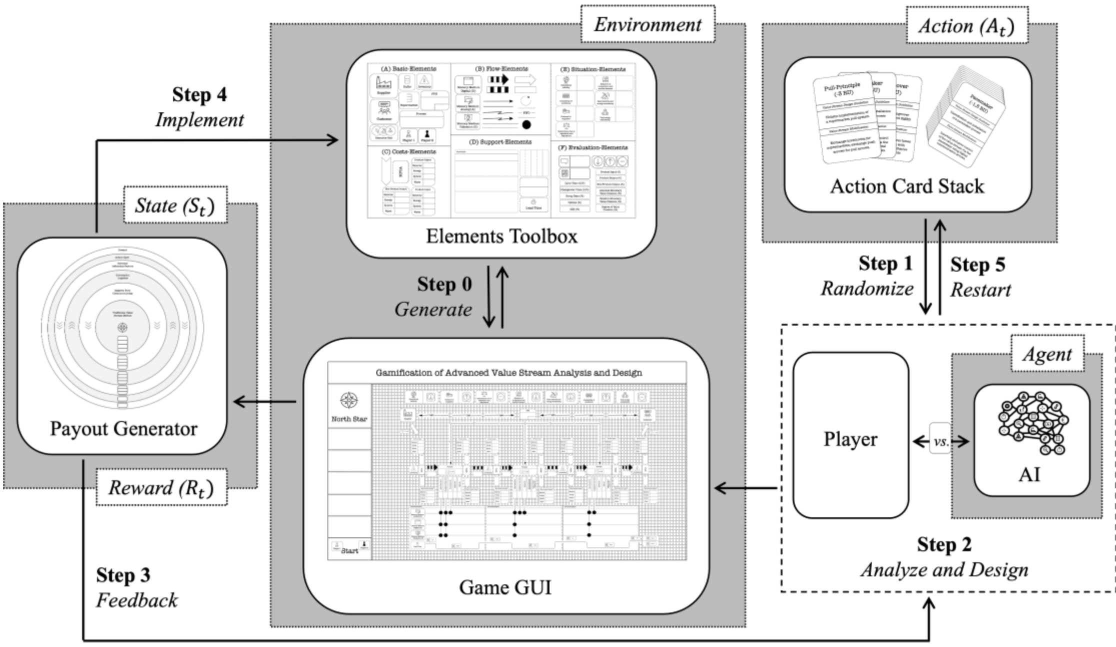

Figure 4: Five-Step Simulation Game Concept for Game-Based Learning with AI

4.3 Evaluation and Deployment

Considering the size of the game board, the possibilities of moves, the behavior of the opponent, the phases of the game, and the random factor, the game concept presented features more possible states than "stratego". Major driver being value stream graphs variations in the complex value stream graph network associated with the reward function. Resulting complexity of the simulation game is a challenge for traceability of results, computing performance, and practical application. To counteract this complexity, the rules of the game must be designed precisely, the effect of the action cards must be balanced, and transparency must be enhanced to further refine the concept.

For future evaluation of the simulation game concept for AI-enhanced teaching advanced value stream analysis and design presented in this paper, an empirical investigation of the usability components effectiveness, efficiency, and satisfaction according to ISO 9241-11 is planned [45]. For this purpose, an evaluation procedure in three steps is intended, while testing the simulation game within the lecture "Digital Lean Manufacturing" in the 5th semester of the program "Engineering and Management" at the Jade University of Applied Sciences. The evaluation procedure initially relevant value criteria and expected performance standards are formulated for the application of the simulation game in teaching. Afterwards, the simulation game is applied with AI-enhanced teaching of advanced value stream analysis and design as component of the designated lecture. As part of the analysis of effectiveness, efficiency, and satisfaction, the students are surveyed, e.g., according to the procedure of Kaiser [46]. Lastly, the survey-based findings are synthesized, and a uniform value judgement is drawn up. This three-step approach allows a first evaluation of the concept and a closer examination of the underlying limitations of the simulation game. Once these have been considered, a second three-stage evaluation in a similar style is to be carried out to validate results, upon success allowing the simulation game to be transferred to full deployment.

5. Conclusion and Outlook

Within this paper the development of a computer-based simulation game concept using game-based learning with AI, which enables advanced value stream analysis and design to be taught to students and professionals in a vivid and motivating fashion, was presented. Objective being to convey methodological knowledge considering AI while explicitly encouraging the development of multi-stage resource-efficient strategies and sustainable thinking. For achieving this objective, a tailored six-step CRISP gamification framework, resulting from merging the six steps to gamification and the CRISP-DM model, was utilized. Discussing of this framework will be part of an individual publication currently in preparation.

Resulting simulation game concept is composed of five-steps including generation, randomization, analysis and design, feedback, implementation, and restart while applying the game components game GUI, elements toolbox, action card stack, and payout generator. To enable game-based learning with AI, these game components were conceptually leveraged to implement five core components of a reinforcement learning model into the simulation game concept. Prospectively, the trained agent can, according to learning preference, be duplicated and be deployed either competitively or cooperatively, creating a unique form of teaching considering personalization, adaptive feedback, content creation, and analysis and assessment.

In continuation of this paper, it is intended to address the challenge of complexity and evaluate the presented simulation game concept featuring game-based learning with AI in accordance with the usability components effectiveness, efficiency, and satisfaction. The evaluation will be carried out as part of the lecture "Digital Lean Manufacturing" and deliver insights into potential limitations by means of an empirical investigation. After a second evaluation, the simulation game can be deployed and enable teaching of advanced value stream analysis and design using incentives such as competitive spirit, success, social exchange and of cause fun factors while promoting cognitive, motivational, and behavioural learning.

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Biography

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