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Generative Design In Factory Layout Planning: An Application Of Evolutionary Computing Within The Creation Of Production Logistic Concepts

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Abstract

This paper describes the creation and application of a generative design approach in the production logistics layout concept creation as part of factory planning projects. Production systems evermore are influenced by an increase of product variants during the planning stages as well as shorter replanning cycles due to higher agility requirements to the production system. Thus, requiring the planner to more frequently conduct the highly complex planning procedure of creating layout concepts for the material supply within the assembly line. Currently, mathematical or graphical assignment methods are executed but are often used disjunct and are not used jointly. Furthermore, today's planning methods are mainly based on manual planning and assignment activities. To address the aforementioned issues, this paper elaborates the application and usability of generative design methods for production logistics planning. As first step the scope and requirements definition for the new production logistics layout application is conducted. Afterwards, generative design, including a multi-objective genetic algorithm, is used to serve as a solution to compile and search through the high-dimensional solution space of all possible logistic layout concepts. Here, layout restrictions and production goals, such as cost and time savings, are reconciled. After the design creation and evaluation by the algorithm, the planner overviews the results and enhances the design parameters until a final concept is reached. This paper concludes with a SWOT analysis of the new planning approach to investigate the used methods, evaluate the impact of the approach on planner's work and identify additional research potentials of using the generative design for other factory planning domains.

Keywords

Generative design; Multi-objective optimization; Factory planning; Production logistics planning

1. Motivation

In the United States (U.S.) during the second half of the 20th century, an estimation by TOMPKINS and WHITE has ascertained that 8% of the US gross national product has been spend on new facilitates annually [1]. Also in Germany, despite the ongoing challenges in the global economy, the number of factory and workshop buildings completed between 2001 and 2018 shows a constant development. Those numbers, although not even including the modification of existing factories, illustrate the fundamental existence of factory planning activities. [2]

In the field of planning manufactories, layout planning and therefore solving the facility layout problem (FLP) stands out as it represents not only one of the utmost essential processing steps in the overall process of factory planning but also interrelates with many other components of factory planning [3]. As major part of factory planning and the Aachen Factory Planning Framework, layout planning handles the arrangement of the operational functional units [4]. This spatial assignment is carried out several times during the full factory design (e.g. for the coarse and detail planning or the ideal and real planning) and at different levels [5]. Its importance is shown, since an effective layout helps to improve the business performance and can reduce up to 50% of total operating expenses [1]. On the other hand, an ineffective layout can result in up to 36% more material handling costs [6]. A further important part of factory planning and very closely linked to the layout planning is the design of the production logistics. As interface between the warehouse logistics and the assembly, the related processes are required to handle the highest amount of diversified and individualized parts and discuss their transportation [7]. In recent years, the planning frequency is increasing due to changes in the market and shortened product life cycles [8].

This research starts by looking at the current status of designing factory layouts and solving the FLP. Then, it develops a new production logistic layout planning approach and tool using prevailed software engineering methods that combine a suitable genetic algorithm with user willingness. The goal of the application is to be able to interact more closely with the practice and to conduct future research directly application-oriented.

2. Literature review FLP and Production Logistics Planning

The target criterion solving the FLP is the optimal arrangement of a variety of objects within a specified area [4]. The various applications of layout planning within the entire planning process are defined by PFOHL. He regards the outer level of layout planning as the internal locations for production segments. Below, he names the determination of the locations of the production units within the production segments. This means the arrangement of the production units such as machines and working stations, but also storage areas. Here, the interrelation between the layout planning and the production logistics becomes apparent. Once discussing the concept of the material supply one uses arrangements for the storage areas and vice versa. [9] In order to narrow down the subject area of factory planning, focus in this paper is laid on depth and not the degree of the dispute with the research field. Notably, the arrangement of objects within the material supply area, therefore the provision area in front of the assembly station, are looked at.

KOOPMANS and BECKMAN were first to define the problem in research and science. Here, under the name of FLP, it is classified a classic computer science problem. Its task is the arrangement of objects within a given area following the material flow between them while certain constrains are fulfilled and objectives are given. [4] Therefore, for finding the best solution, often the principle of form follows flow is used [10]. KOOPMANS and BECKMAN formulated the problem as a quadratic assignment problem (QAP) [4]. Others have formulated the problem as a quadratic set covering problem, a linear integer programming problem, a mixed integer programming problem and a graph theoretic problem [11]. The literature has added in defining it as a NP-Problem [12]. The FLP is either applied for equal areas or unequal areas and extensions were made to add more than one target criteria and therefore have multiple objective functions as this better reflects the reality [13]. From the beginning of research, many algorithms have been developed to solve the problem and various papers were published surveying the existing algorithms. If one wants to access more literature regarding this topic, one can refer to Hosseini or Kusiak [14, 11].

To allow a concurrent engineering approach, in conjunction with layout planning, this parts looks at production logistics. Following LUCZAK, the literature subdivides the logistics of a company into procurement logistics, production logistics and distribution logistics [15]. According to the flow of goods within the enterprise logistics, the productions logistics is incorporated between the procurement and the distribution logistics and connects them with each other [9]. The production logistics planning includes the design of the logistic system within the factory starting at the incoming goods area, going through the internal material supply to the outgoing goods area. This includes the required logistical areas, storage and transport means as well as load carriers, supply principles and buffer sizes. [16, 17, 9]Those aspects all aim to achieve a supply of material at their designated areas. Depending on the size of the cooperation, it can be useful to divide the production logistics after spatial measures. Here, the areas covered can be divided into an intra-apparative (inside individual production plants), an in-house, an inter-company and an inter-plant logistics. In the course of this work it is decided to focus only on the intra-apparative area. [18] LOTTER AND WIENDAHL describe the supply of materials as essential for the delivery time, delivery reliability and thus as a logistical success factor [19]. The goal is the optimization of the internal material and information flow to and between the production sites [7, 20].

Despite increasing digitalization and extensive computer support also in factory planning, currently, the process of newly designing or modifying layout concepts including the production logistic aspects still requires manual handling, which makes it a very unpleasant task [21].

To face the circumstances, an analysis of artificial intelligence approaches and paradigms has taken place and evolutionary algorithms and especially genetic algorithms have turned out to be most matching to the FLP. Especially, generative design (GD) as application-oriented tool using genetic algorithms in engineering shows great potential in factory planning. Therefore, in the following GD is further presented.

3. Introduction: Generative Design

AGKATHIDIS points out the fact that there is no clear definition of the term „generative design“. He describes it „[…] as a design method where generation of form is based on rules or algorithms […]“. [22] More engineering related, MCKNIGHT defines GD as „[…] the process […] mimicking natures evolutionary approach… to quickly explore thousands of design variants to find the best solution[...]“ [23].

MCKNIGHT describes the GD process in four phases. During the first phase the person in charge is required to define the input parameters and additively the goals. Possible parameters include constraints or properties of the materials. Often goals contain the mass and volume, which can in many cases be linked to the costs. The data can be of qualitative and of quantitative nature. The second phase uses computational power, sometimes extended by cloud computing, and various algorithms to generate a vast number of designs. This phase can be broadened by adding performance analysis for each design. The third phase includes an iteration process by the engineer. After obtaining the results from phase two, the various concepts are studied and possibly parameters and goals are adapted. In addition with AI, the human iterates new concepts until a most relevant solution is identified. The last phase describes the aftermath to the GD process. Combined with additional tools and methods the final design is used to solve the general problem. [23] The above described phases slightly amended by VILLAGI ET AL. are presented in Figure 2.

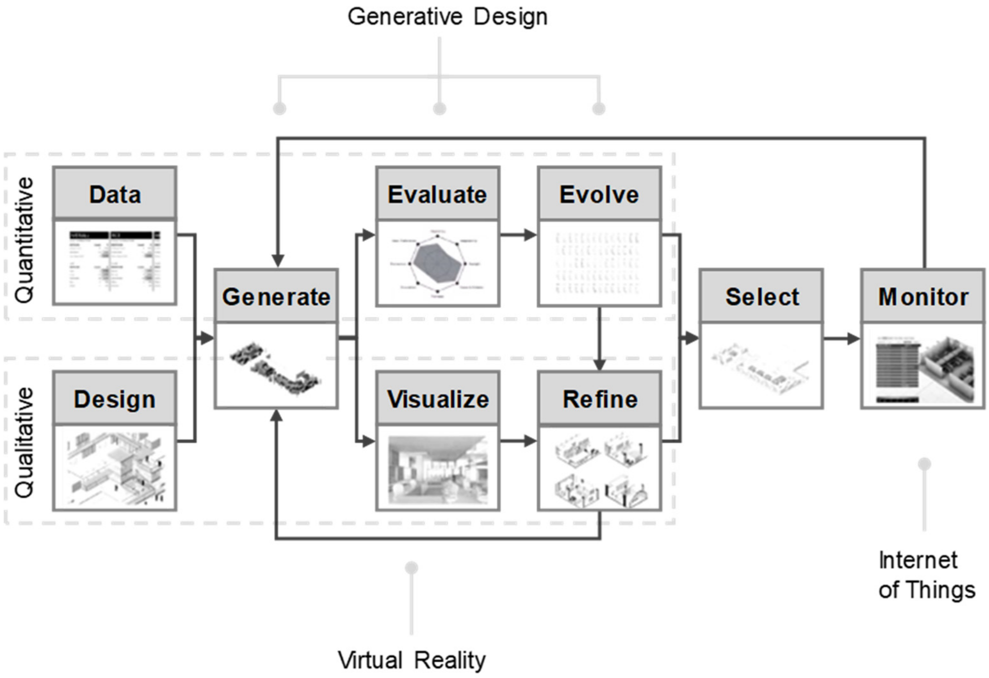

Figure 1: Generative Design Approach following [24]

Here, next to the GD aspects, also possible engagements and levers of virtual reality and the Internet of Things are shown. Nowadays, research of GD has ventured forward into the architectural field [25 – 27].

Next, a methodology has been developed which creates a GD tool for the application within the production logistics layout planning.

4. Methodology

This paragraph describes the methodology which makes use of software engineering and in particular of the stages of the waterfall model in a modified form which are seen in the Figure 2. In order to reach the aim of a GD tool for layout planning, it is necessary to specify the requirements. Within this first stage of the waterfall model, the requirements were analyzed and listed in a threefold way. First, the planner as user sets certain standards for the tool. The tool is supposed to fit to the current knowledge of the planner and respects its abilities of using software and computer support. Second, the integration of the genetic algorithm needs to be considered. The functionality of the tool in relation to the algorithm requires to take a look on how the genetic algorithm works in detail and how it then can be implemented within the software. The system itself is required to run a genetic algorithm for its evolvement of the layout concepts. By changing the inputs, calculating specified goals, evaluating and then evolving various concepts and performing the optimization given by the genetic algorithm, a high number of layouts is created and optimizations are driven. The layout creation should also include a randomization of possible layouts and therefore have the possibility to not use any optimization algorithm. For the ability of running the genetic algorithm, the system needs input parameters, constrains and fixed goals. Since this tool applies in the creation for the layouts of the assembly station provision area, a detailed analysis of the layout related elements including the aspects from the production logistics topic is necessary. As the purpose of the instrument is to create a number of possible layout concepts for factories considering production logistic aspects, which are depending on specific rules and objectives, also those have to be defined clearly and scientifically derived from appropriate literature. Most important, the tool needs to be compatible with the requirements from the layout concept creation process.

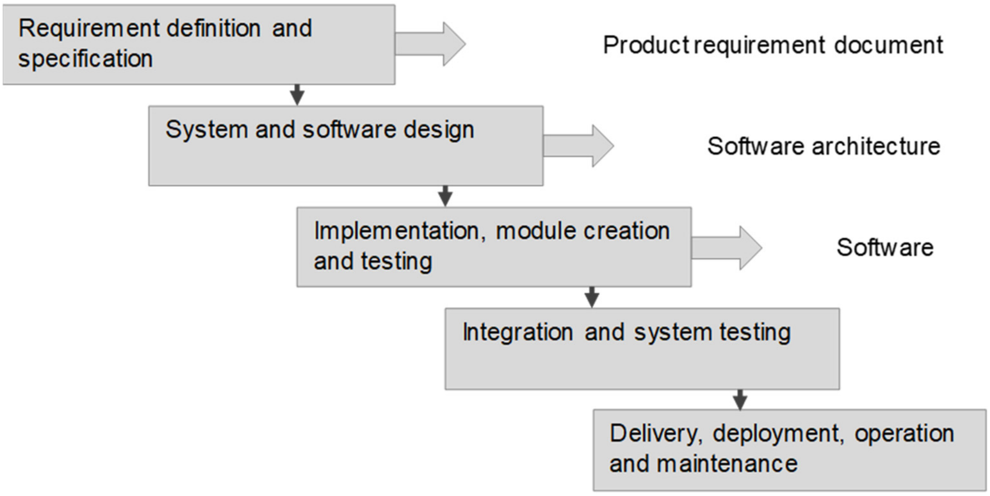

Figure 2: Waterfall model methodology to create factory planning supporting software

For this reason, following elements were assessed more in detail: potential layout contour, number of components, buffers within the storage, production matrix on a time axis, material supply strategy, means of conveyance for the transportation, conveyance aids and area of storage. These are not mentioned as part of this publication due to these areas being common for every production and have been investigated using experience and standard literature.

Next, for combining the mentioned elements to the layouts, multiple objectives and restrictions are found in the factory planning literature. Here, the two criteria of material flow and costs are further presented, while it should be feasible for the tool to be expandable on more aspects. KETTNER ET AL. analyze the process of arranging the operational tools within the factory and they conclude that the production flow must be observed. They asses the four main components of the production flow as material, personnel, information and energy flow. Because the material flow is determined as the main cost driver, most methods focus on the minimization of transportation cost. Inter alia, in the internal location planning, the main goal is to minimize the transport costs [28]. Therefore, as most methods only allow one optimization criterion, the material flow is the chosen one [5]. During the layout planning of a material flow system, the goal is to find favorable spatial arrangements for the material flow relationships up to finding the minimum cost configuration. To measure and rate the costs for transport ARNOLD and FURMANS propose using the distance and the throughputs [29]. Since transport is the moving of objects and transportation referring to TAKEDA this is a way of waste, the goal is to minimize the distance covered by the loading carriers [30]. Those discussions deduce to having a minimized transport path as target. In addition, the required space is a highly important commodity as it links directly with area costs. In this case, either the space is given, or it is to be calculated. Therefore, another objective is the degree of used space and the goal is for it to be kept low [31]. On the one hand there is a given space which is then claimed by several entities. On the other hand, the space is to be estimated and then directly linked with the price for purchase or rent of a piece of land. In either occasion, the target is to require the smallest space possible. Another target for the economic efficiency is the goal of keeping the investment low [32, 19]. Also, a low tied capital can be targeted with a stock as little as possible [33]. Therefore, the goal of the GD instrument is to lower the tied capital or the investment costs. Additionally, the target is to keep the labor costs down by reducing operational times per operation.

Creating the product requirement document, it is indispensable to consider the system itself, but also its influence and connection with and from the outside of its boundary. For this reason, this second step discusses the design of the overall system and the software itself. Here, the GD tool on a high and on a lower level must be represented and the software architecture acts as outcome. For the high level of designing the tool, as a system within the factory planners task and delineated within the modules from the Aachen Factor Framework, the use case diagram as one of fourteen UML diagrams is well suited. Since the conception of the tool orientates towards GD, the model mentioned above is taken for the method design of the tool. Here, as aforesaid, currently the planner collects necessary qualitative and quantitative data and then creates suitable layouts per hand or with diverse but not sufficiently automated tools. Possible layouts with positive features are then further looked at and analyzed mathematically, before a final layout concept is decided on. Thus, then getting implemented until modifications come up. Using the GD approach from architecture, the phase where the planner creates suitable layouts per hand, the planner now is supposed to be using a GD tool.

First, the factory planner collects the qualitative and quantitative data and uploads the data into the system. Inside the system, the tool automatically generates a high number of layouts via iteratively creating, evaluating and evolving the layouts applying a genetic algorithm. Finally, a number of various designs is presented. Thus, the factory planner has to select one or more layouts which are then exported and can be used within other tools or can directly be implemented. In the beginning, the user simultaneously defines the targets of the layout and inputs the qualitative and quantitative data. This data for the above explained application consists of the layout, the possible material supply strategies, the possible means of conveyance, the possible conveyance aids, the possible provision technology as well as all restrictions and constraints and last the production numbers. The next step is the creation of the layout. Here, a possible selection of inputs is collected and a random layout is designed based on the production numbers and the restrictions and constrains and directly evaluated by the defined goals. This layout is then saved including its collected and calculated data.

In the next step the genetic algorithm changes the inputs and the loop runs again. When a specified amount of loops is done and different layouts are developed, the loop stops and the selection is presented to the factory planner.

In the third step the software was constructed and coded according to the requirements and the software architecture from the proceeding step. Before programming, the exact implementation of the design was broken down to various modules and those were then being described and later programmed.
In the fourth step, the modules were combined and linked to each other. Also, within this step the explanation of how to get the tool running and where it fits in the overall planning cycle of the layout creation was given. This included the explanation of the general usage of the software for the planner. Some of the other activities within this step involved testing the system as a whole on compliance with the requirements and restrictions. As last part of the waterfall model, the system was then put into practical use. A first use case of the application is explained in the following chapter.

5. Use case / Application

Since there are many existing programs on the market which enable to not fully rewrite a new software and still fulfill the requirements, this work rather extends existing VPL tools. In the course of this work, Dynamo as part of the Revit toolkit is used. Here, Revit 2020 and the included Dynamo 2.1 serve as visualization, displaying and visual programming tool and Project Refinery Beta enables the GD ability.

As use case, this work used the workshop production layout problem delineated by WÄSCHER, which is then applied within the visual programming code. This problem uses a delimited area (layout boundary), a set of arrangement objects (AO), material flow relationships between the AOs, additional conditions such as relative or absolute installation conditions. The spatial arrangements can then be valuated using a set of destinations such as transport distances and transport costs. [34]

In the next step, the above deployed process is running a randomization creation phase resulting in 300 different possible layouts. For applying a genetic algorithm for an optimization of the concepts, tests were done, but show that the time required to optimize all outputs takes comparatively long. Therefore, within this use case, the objectives are randomized and not archived through the application of a genetic algorithm.

Nevertheless, this optimization is possible and doable with small modifications and enough time resources and within existing software, which enables the establishment of the above created software methodology. Figure 3 shows part of the results.

Figure 3: Extract of possible layout concepts

The application and the results show, that for creating a variety of different possible layouts, the developed tool serves as a feasible solution. The GD approach from architecture therefore is applicable and suitable for factory planning, since all the requirements are fulfilled while all constrains are satisfied. Thus, the factory planner is now able to view the data and decide on the best possible layout. Nevertheless, the designs show the possible layouts but are not equipped with a visualization of the output figures. So in the first step the output figures need to be generally designed but also determined and weighted for every specific planning case. This could be improved in future simulations. A qualitative evaluation by the planner is furthermore possible and subsequent arrangements can be done to the constraints and restrictions. Thereafter, a new running of the algorithm or a new randomization can be started and even more concepts can be created and improved. With this, the results from RIPON ET AL. are successfully integrated into a tool and an iterative solution for the planner to create layouts exists [35]. The step of applying visual programming to create the use case and all the above explained modules so far was not as easy as expected. Many restrictions within the software made it necessary to work with simplifications and work arounds. Thus, creating high efforts for the planner. Especially, as this use case is quite simple, still much work was required and further extensions of the case probably come with even higher effort. In general, it turns out that, although the software is used in the field of architecture, there is still a lot to be done in the much more complex area of factory planning. Yet, for this specific use case, the implementation of the tool application in the workshop case was successful.

6. Conclusion

At the end of this study, a SWOT analysis of the new planning approach investigates the created methodology and lists additional research potentials of using the GD in other factory planning domains.

The whole dispute was started with the idea of applying GD in the area of factory planning. In retrospect, this was quite dangerous as it does not confirm with the scientific approach. Normally, a research gap is deduced in the beginning and then possible solutions are searched and created. In this case, it was the prerequisite that GD is applied and the whole construct of this work was then build around this idea. The risk in this attempt is, that the research can come to the result, that GD is not even the best solution or any possible solution. Luckily, the results do not confirm this risk, whereby an influence cannot be excluded by the sequence followed here. The business demand of creating a tool which helps the factory planner on choosing the suitable material strategy and its production logistic concepts on the one hand is comprehensible, although more research is required to fully examine the whole spectrum of possible solutions.

One of the weaknesses of this work is clearly the amount of simplifications. Here the area should have been narrowed down even further in advance. Furthermore, the dispute of AI is far not deep enough and the holistic view requires a further debate with more literature and experts in the field of AI. The use case shows, that many weaknesses exist also in the existing software. The disadvantages of the used software were listed and either the software requires many modifications or updates, or a whole new software is necessary.

Despite those negative aspects, the work gave a first impression on GD within factory planning and therefore starts an interesting subject of research. With modifications and improvements, the tool in the future could help the planner to actually design layouts, which were before unthinkable and furthermore assists in the evaluation phase. This research pictures the feasibility of a software tool to assist the planner and with the use of AI algorithms improve the planner's tasks. Using existing software from another area such as architecture, was helpful in that respect, that it can be built on top of this research instead of requiring to completely redeveloping all the knowledge.

Those strengths create many opportunities for further research as the time is currently right with cloud computing and an advanced level of engagement within this field of research. Many new topics are found which can be worked out to independent works. A study on current papers on the facility layout problem algorithms is required, since the last one is a couple of years old. This work has only touched the topic of genetic algorithms as FLP solutions, this needs a detailed analysis. Apart from this, a detailed analysis why GD from architecture is suited for factory planner (similarity of the two jobs) would be interesting. This can be archived in levels above the planning of the provision area by doing the choice of location, the general construction of building, the arrangement of operating departments or the arrangement of operational functional units. Below, it can be done within the material supply strategy, e.g. material handling and supply strategies are planned automatically or decision of which supply vehicle/ tool to use for which task) or the workplace structure.

Consequently, this work forms a basis for further research work in the entire field of future factory layout design applications. This fundamental new approach to generative design might support the vision of the future factory to become reality faster.

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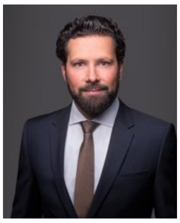

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