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Integrated automatic configuration system for modular strongroom: Development, integration and implementation

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ABSTRACT

The paper presents the Integrated Automatic Configuration System (IAKS) for modular strongroom (MSR). IAKS encompasses the processes of generating possible product variants, choosing the optimal configuration (variant) of the product, and detailed CAD design of the product and technological process. The system is composed of nine interconnected modules that facilitate the automation of various design phases. The modules for conceptual configuration, optimization, and CAD configuration, which were previously partially published, are herein briefly described and presented as part of the whole system. The primary objective of the present study is to integrate all modules, thereby enhancing the efficiency and automation of the MSR design process. In response to customer requests (CRs) and security requirements, IAKS automatically designs the optimal MSR. The developed method and software solution were implemented through a case study, which confirmed its applicability in the automation of the MSR design process. The primary benefits of this application include a reduction in design time, an elimination of design errors, a decrease in production time, an enhancement in product quality, and a reduction in product price.

KEYWORDS

Automatic configuration, Modular products, Modular strongroom, Optimization, CAD design.

1. INTRODUCTION

The market's demand for rapid changes necessitates flexible, adaptable solutions that facilitate swift adjustment to new conditions. The MC (mass customization) strategy is a solution that meets individual customer requirements (CRs) while leveraging the economies of mass production. The application of modular design enables the system to respond quickly to changes and upgrades.

Strongrooms are produced in a combination of methods, including massive construction, modular construction, and a combination of these approaches [1, 2]. Modular construction utilizes standard components and modules, which allow for flexibility and optimal room configuration tailored to customers' specific needs. This approach also facilitates installation in existing rooms or on higher floors, enhancing versatility and convenience. It also facilitates more efficient design by reducing time and eliminating design errors [1, 3].

Modular strongrooms (MSR) provide a high level of safety and flexibility in design. Its modular design allows for customization of size and specifications to meet customer requirements while ensuring basic safety requirements [4]:

- Burglary resistance,
- Fire resistance,
- Safety from flood (i.e., water penetration), and
- Resistance to different types of radiation.

The fundamental CRs when designing the MRS include the shape and overall dimensions of the MRS, as well as the resistance grade of the MRS according to the EN 1143-1 standard. These requirements also encompass the position, dimensions, and direction of the door opening. Additionally, there are numerous CRs that result in substantial variations in the number, shape, and dimensions of individual modules [4]. Consequently, each MSR is regarded as a new project.

Conventional methodologies are predominantly employed in the design of MSR. The implementation of CAD (Computer-Aided Design) systems in the generation of 3D models of MSR significantly streamlines the documentation process. However, the presence of errors or inconsistencies in the design remains a persistent challenge. This necessity arises from the recurrent requirement for modifications to align with the customer's specifications, necessitating the manual adjustment and update of numerous parameters. Furthermore, certain decisions need to be made to ensure the design is correct and functional. To solve that problem, we need an **integrated system** that's automated and combines:

- Efficiency and speed (let quickly generate and test possible product configurations);
- Selecting the optimal product configuration (based on specific CRs and criteria like production time, price, and quality);
- Detailed CAD design of the optimal product configuration.

These systems really cut down on design time and get rid of human errors, which leads to a lower product price.

This paper presents the **Integrated automatic configuration system for MODULPRIM type MSR** (**IAKS MODULPRIM**). The goal is to present IAKS MODULPRIM as a complete solution for designing MSR. The principle of operation of all modules, as well as the way of their integration into one functional system, is presented below. Also, the advantages that IAKS MODULPRIM brings in terms of time, costs, and quality were analyzed.

2. STATE OF THE ART

A variety of CAD software is employed in the domain of product design, such as Autodesk Inventor, SolidWorks, Pro/E (Creo), CATIA, and Siemens NX. Basically, these CAD software does not have the capability for automatic product configuration, but this can be achieved through the use of their supplementary modules (iLogic, DriveWorks, Knowledge Workbenches, Knowledge Fusion, etc.) or by integrating with external tools [5].

A certain number of papers address the integration of CAD systems with external tools, such as Microsoft Excel spreadsheets. This connection enables dynamic updating of CAD design parameters and automatic generation of 3D models based on data from tables. The utilization of these tools fosters adaptability and expedites product configuration, facilitating the customization of designs with particular requirements. This, in turn, contributes to the acceleration of the product development process and the minimization of design errors and expenses. Grković et al. [4] propose a platform for automatic configuration of MSR, based on parametric and variable design through the integration of CAD software (Autodesk Inventor) with an Excel spreadsheet. In response to a CRs, the Excel spreadsheet automatically generates product variants and calculates all pertinent design parameters. These parameters are subsequently automatically imported into the CAD software to adjust 3D models. Gembarski et al. [6] demonstrate how the spreadsheet-driven CAD models can enhance adaptability and product optimization in the configuration process of cultivators. This integration facilitates design automation and reduces the necessity for manual model adjustment in CAD software. Geren et al. [7] developed a parametric CAD system for automatic dimensioning of ball joints in automotive steering systems. This system utilizes expert knowledge and feature-based computer-assisted 3D modelling in CAD software Pro/E (Creo). The implementation has demonstrated its practicality in generating different configurations tailored to the requirements of OEM manufacturers.

The integration of engineering knowledge into CAD systems through Knowledge-Based Engineering (KBE) and Knowledge-Based Design (KBD) facilitates automation and optimization of the design process. KBD integrates this engineering knowledge directly into the CAD environment, thereby enabling the automation of routine tasks and the reduction of errors. Gembarski et al. [8] investigation focused on the examination of disparate approaches to integrating CAD systems and KBE. He demonstrated the fundamental capabilities of integrating KBE with the CAD system (Autodesk Inventor).

Gembarski et al. [9] demonstrate the automation of the design process through the integration of knowledge-based CAD systems with algorithmic modeling. The proposed approach utilizes rules derived from domain knowledge in conjunction with parameterized algorithmic models to facilitate the efficient generation and adaptation of technical solutions. Reddy and Rangadu [10] developed a system for parametric CAD modeling of spur gears based on KBE. In the CAD software, specifically SolidWorks, an add-on was developed that incorporates an input mask and a design calculation by the rules of the AGMA (American Gear Manufacturers Association).

A multitude of papers underscore the significance of models grounded in optimization algorithms and multi-criteria decision-making within the domain of automatic configuration. Zhang et al. [11] developed the COMB algorithm, which was designed for the optimization of configurations of modular space stations. The focal point of their research was the implementation of evolutionary algorithms (GA) to engineer an efficacious design solution for automatic module adaptation. Wei et al. [12] developed a mathematical model to optimize product configuration in mass personalization, taking into account performance, cost, and production time. On the example of air compressor configuration optimization, they demonstrated the application of the improved NSGA-II algorithm and the fuzzy method for decision-making when determining optimal configuration. In their study, Đorđević et al. [13] present a model that utilizes the Analytic Hierarchy Process (AHP) and Simple Additive Weighting (SAW) methods to select the optimal MSR configuration. This model facilitates the selection of the optimal configuration based on multidisciplinary criteria, thereby reducing production time and costs while enhancing the quality of the final product. Zhang et al. [14] investigated the potential of integrating sales, product, and manufacturing configurations to enhance companies' capacity to provide customized products. This approach has been demonstrated to generate a greater number of possible alternatives for products and production processes. Consequently, evaluation models have been developed with the objective of selecting the most suitable option.

A thorough review of the literature reveals a clear necessity for an integrated automatic configuration system, one that would serve to unify variant generation, optimization, CAD design, and decision making. IAKS MODULPRIM was developed as a precise response to these challenges, enabling the automation of the entire MSR design process.

3. STRUCTURE AND INTEGRATION OF IAKS MODULPRIM

The development of an Integrated Automatic Configuration System (IAKS MODULPRIM) was motivated by the necessity of aiding in the decision-making process that occurs during the selection of the optimal configuration of an MSR. The methodology encompasses the procedures for generating possible MSR configurations, selecting the optimal configuration, and detailed CAD design of products and technological processes. The developed IAKS MODULPIM has the following characteristics [13]:

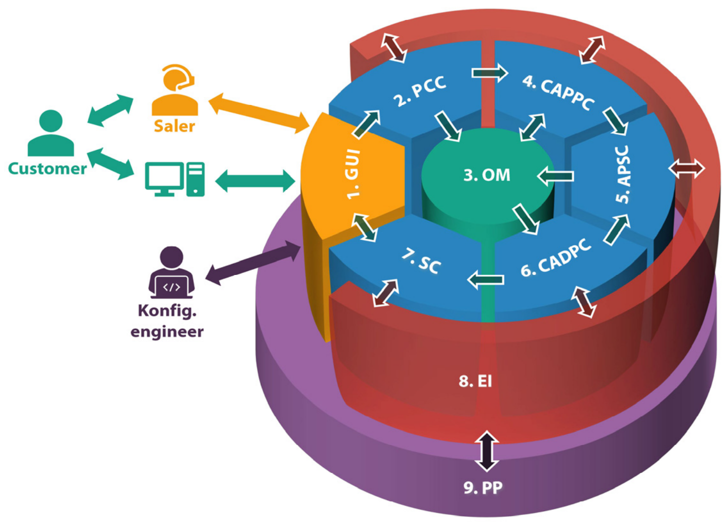
- A set of feasible product configuration variants is generated based on the CRs and the developed product platform;
- The selection criteria should be designed to align with the characteristics of the product from the perspective of both the customer and the manufacturer. From the customer's viewpoint, the criteria should emphasize the importance of a high-quality and inexpensive product that is produced in the shortest possible time. From the manufacturer's perspective, the criteria should prioritize cost-effective and efficient production with minimal errors;
- The objective criterion functions are defined in advance and are given in parametric form, i.e., depending on the set of parameters defined by the product platform;
- The selection of the optimal product configuration is performed by applying some of the multi-attribute decision-making methods;
- The selected alternative is employed for the subsequent stages of the product's CAD design and the development of its technological processes. It is also utilized in the creation of an operational plan for the product's implementation and the delineation of the offer that is delivered to the customer via the sales configurator and user interface;
- As previously stated, the aforementioned processes are integrated and automated.

The IAKS MODULPRIM system is composed of nine distinct modules, which are illustrated and delineated in Figure 1. The central module is the optimization module, while other modules are arranged around it and are logically and functionally connected into one whole [3].

3.1. Graphical User Interface

The **Graphical User Interface (GUI)** is a module that facilitates communication between the user and the proposed system. The participants in the communication are as follows:

- the end user (customer);
- sales staff;
- configuration engineer.



1. **GUI** - Graphical User Interface
2. **PCC** - Product Conceptual Configurator
3. **OM** - Optimization Module
4. **CAPPC** - Computer-Aided Process Planning Configurator
5. **APSC** - Advanced Planning and Scheduling Configurator
6. **CADPC** - Computer-Aided Design Product Configurator
7. **SC** - Sales Configurator
8. **EI** - External Interface
9. **PP** - Product Platform

Figure 1: General structure of the IAKS MODULPRIM with named module [3]

The end user is empowered to define their requirements directly with the assistance of this module, enter the necessary input data regarding the product, and request clarifications regarding the final solution. The GUI has been adapted to the user, thereby eliminating the need for training in its use. The GUI assists the user in defining their requirements by posing questions and providing answers, ensuring that the system receives information in a format with which it is familiar. The final result of the configuration process in IAKS, from the user's perspective, is the offer that is obtained from module 7 (Sales Configurator) and is subsequently transmitted to the customer via the GUI.

In the event that the customer lacks the capacity or interest in entering data directly via the GUI, the sales staff is authorized to execute this task on their behalf. Furthermore, the sales personnel are obligated to formally present the offer and the requisite documentation to the customer, while also offering supplementary clarifications as required.

A **configuration engineer** is a professional who specializes in the field of product configuration. Through the use of an interface, these engineers analyze and evaluate various configuration variants, analyze the optimal solution, and final reports that are subsequently transmitted to the customer and production.

3.2. Product Conceptual Configurator

The Product Conceptual Configurator (PCC), as illustrated in Figure 2, automatically generates potential product configuration variants based on CRs. The system comprises a converter and a generator of feasible product alternatives [15]. The converter transforms order data (CRs) into technical data, which is then used to configure the MSR.

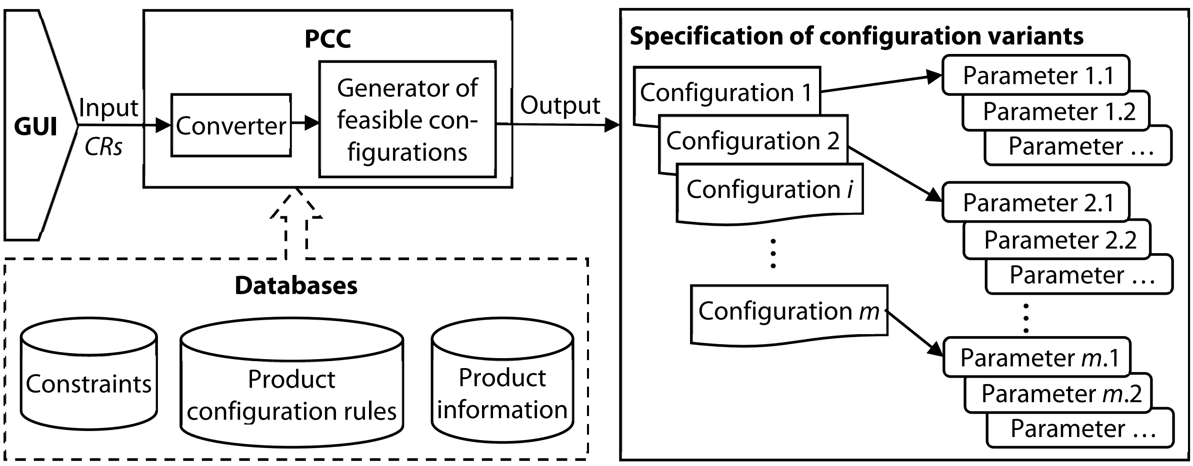


Figure 2: The structure of module 2: Product Conceptual Configurator [15]

The configuration task of this module is to configure all possible conceptual product variants that meet the individual CRs, based on product configuration rules and a database of the product, its modules, and components, and respecting the defined constraints. This component is incorporated within the generator of feasible configurations. The databases comprising rules, modules, and constraints are located in the product platform (Module 9) and are accessed via an external interface (Module 8).

The output of this module is a specification of parameters that define the configuration of the MSR, modules, components, materials, etc. A comprehensive description of the MSR conceptual configurator is provided in [15].

3.3. Computer-Aided Process Planning Configurator

Computer-Aided Process Planning (CAPP) liberates the designer from routine and time-consuming operations, enabling a greater commitment to critical decision-making during the design of technological processes. These decisions encompass defining operations, operations and processing sequences, selecting machinery, tools, accessories, and processing parameters. This contributes to a significant reduction in design time and costs, equalization of quality levels, more productive and economical technological processes, and increased productivity [16]. The design of CAPP is a highly intricate process that is contingent on numerous parameters. Consequently, there is an absence of a universally applicable CAPP system that is suitable for straightforward and extensive implementation in industrial settings [17].

The fundamental input data required for the CAPP system encompasses product-related information, available production resources, projected production volumes, and a range of techno-economic requirements. Product information, primarily conveyed through two-dimensional drawings and three-dimensional product models, offers insight into geometry, topology, dimensions, tolerances, materials, and the quality of machined surfaces. This information is essential for manufacturing, assembly, and the control of the product. The available production resources encompass fundamental information regarding various components of the production system, including fixtures, machining systems, tools, accessories, and gauges.

The structure of the **Computer-Aided Process Planning Configurator (CAPPC)** is illustrated in Figure 3. It is important to acknowledge that, in addition to other input data, CAPPC is the recipient of information containing data on all feasible alternatives (A_i, p_k^i) of the product that is generated in module 2.

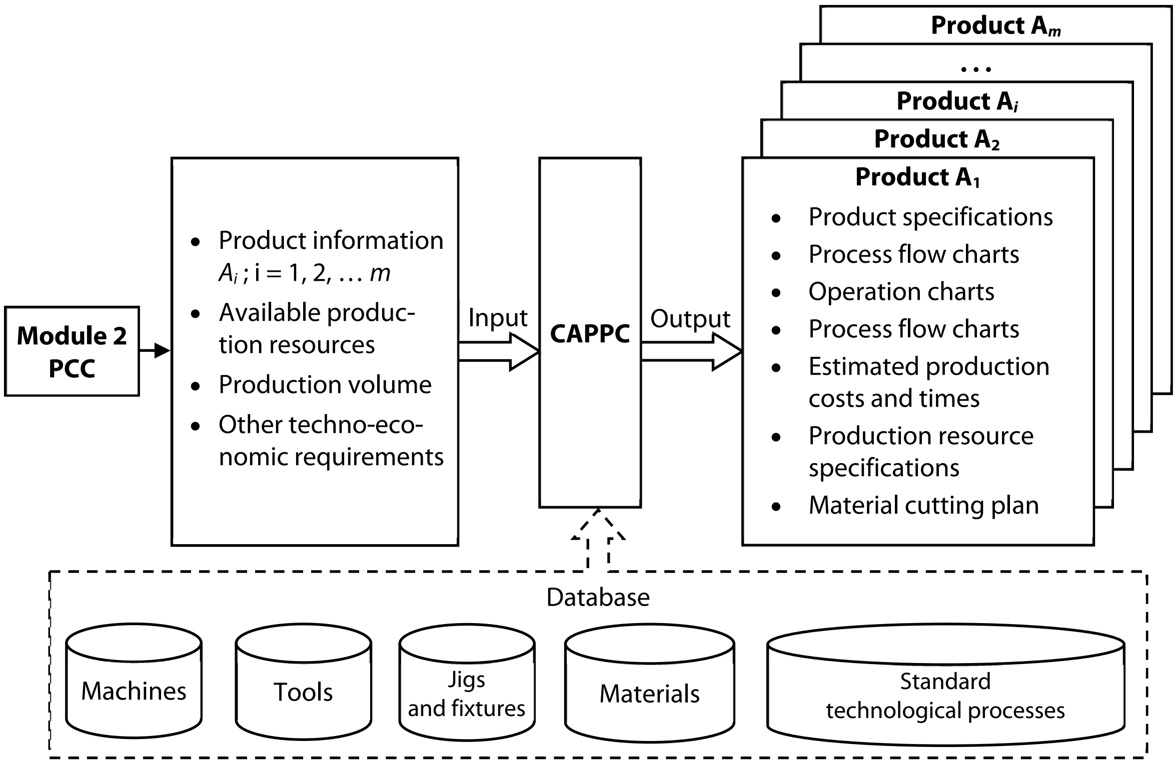


Figure 3: The structure of module 4: Computer-Aided Process Planning Configurator [3]

The objective of this module is to generate data pertaining to time, cost, and quality for all ***m*** product alternatives. These data will subsequently be utilized in Module 3 to calculate the values of the objective functions. Consequently, the technological documentation and information necessary for planning, managing, and implementing the production process are obtained. This may include product specifications, the content of technological processes, operation charts, process flow charts, calculated production costs and times, specifications of production resources, and other relevant elements [3]. Subsequent to the selection of the optimal product configuration, the output specifications from CAPPC for the selected configuration are forwarded to module 5. On the basis of these specifications, production planning, management, and implementation are carried out.

3.4. Optimization Module

In the process of designing or configuring a new product, optimization is a pivotal stage. The developed system pertains to modular products, defined as products that are assembled using standard modules. The implementation of a modular product system necessitates the fabrication of components and modules in sufficiently large series, production with an acceptable number of technologies, tools, and accessories, a reduced amount of information, etc. [3]. Consequently, it is hypothesized that the designs of the available modules and their components have already been optimized, that the technological processes of manufacturing and assembly have been standardized and optimized in terms of processing modes, costs, processing time, etc., so that part of the optimization is not considered in this paper.

The optimization module's primary function is to execute automatic multi-criteria evaluation of the product, considering factors such as costs, quality, and production time. This evaluation is achieved through the implementation of multi-criteria decision-making methodologies. The input data for this module are the alternatives generated in module 2 (PCC) with the corresponding parameters defining the product, its modules, and components (Ai, pki). The formation of the criterion functions is generated in module 4 (CAPPC) based on the following:

- Standard technological processing procedures, time, and labor standards were followed;
- The required number of sheet metal panels for creating all module positions was calculated based on a special algorithm and program developed in the MATLAB 2019 software package;
- A database containing the price of materials and finished components, labor cost, etc., was created;
- An analysis of the dependence of quality and errors on the type and parameters of the module was conducted.

The output from this module comprises the data on the selected product configuration and the specifications of the associated parameters (A^{opt}, p_k^{opt}). The configuration of the optimization module, inclusive of inputs and outputs, is depicted in Figure 4.

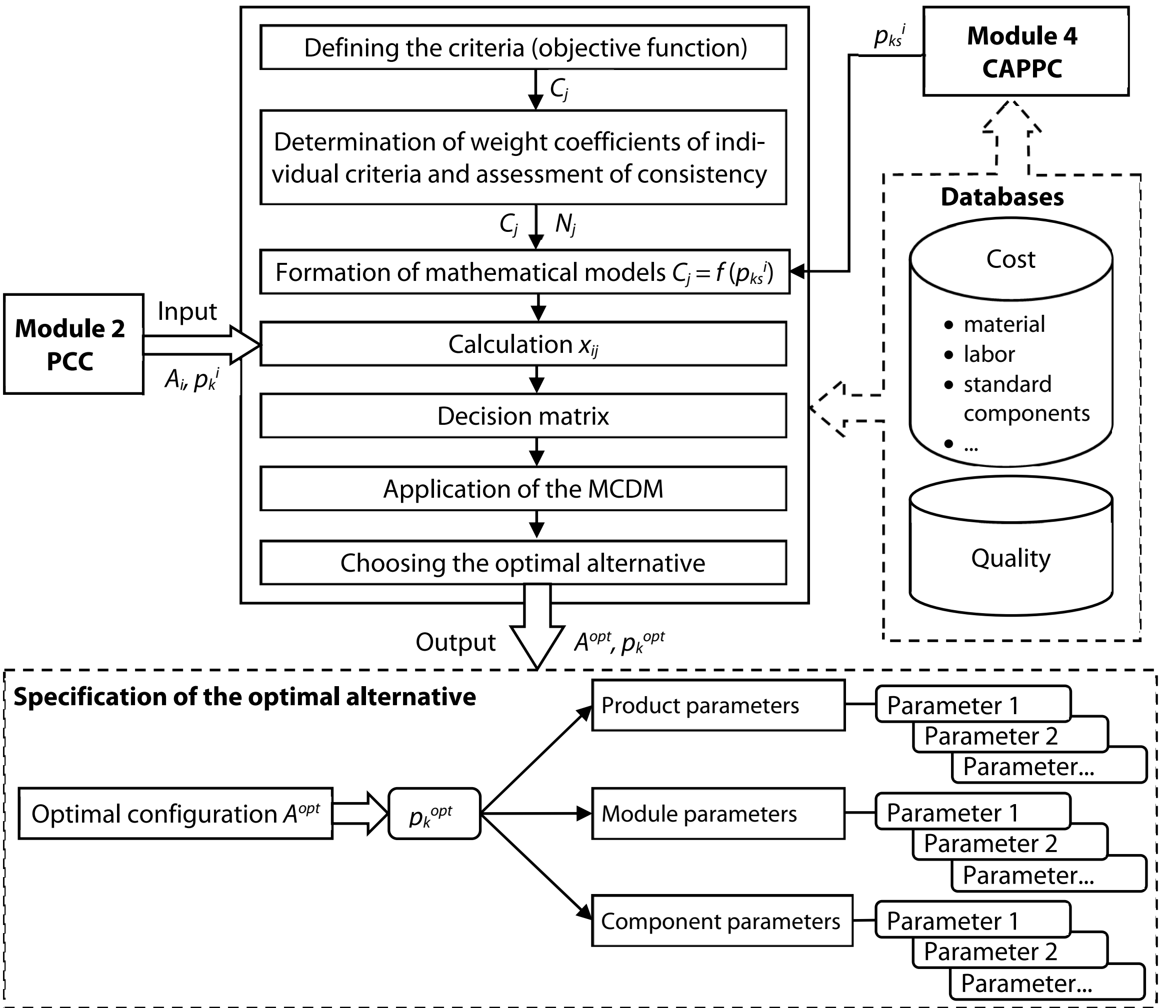


Figure 4: The structure of module 3: Optimization Module [13]

A thorough exposition and delineation of the functionality of the optimization module are provided in the paper [13]. By selecting the optimal product configuration, the output specifications from this module are forwarded to module 6 (**CADPC**) for detailed design of the optimal product configuration.

It should be noted that the **optimization module** is a key link in the developed IAKS model. In the case of complex products, where it is possible to generate a multitude of different configurations, very complex mathematical models of the objective functions are obtained. Consequently, it is logically not possible to select the most favorable configuration. The main advantage of the developed system is that, on a multidisciplinary basis, it automatically selects the optimal configuration from a set of feasible configurations.

3.5. Advanced Planning and Scheduling Configurator

The input data in this module are as follows: 3D models and 2D drawings of products, product modules, and components; product components; operation charts; process flow charts; production and assembly time norms, production resource specifications; material cutting plans; control plans, etc. This information is obtained from modules 4 and 6 after selecting the optimal product configuration. The structure of the **Advanced Planning and Scheduling Configurator** (**APSC**) is illustrated in Figure 5.

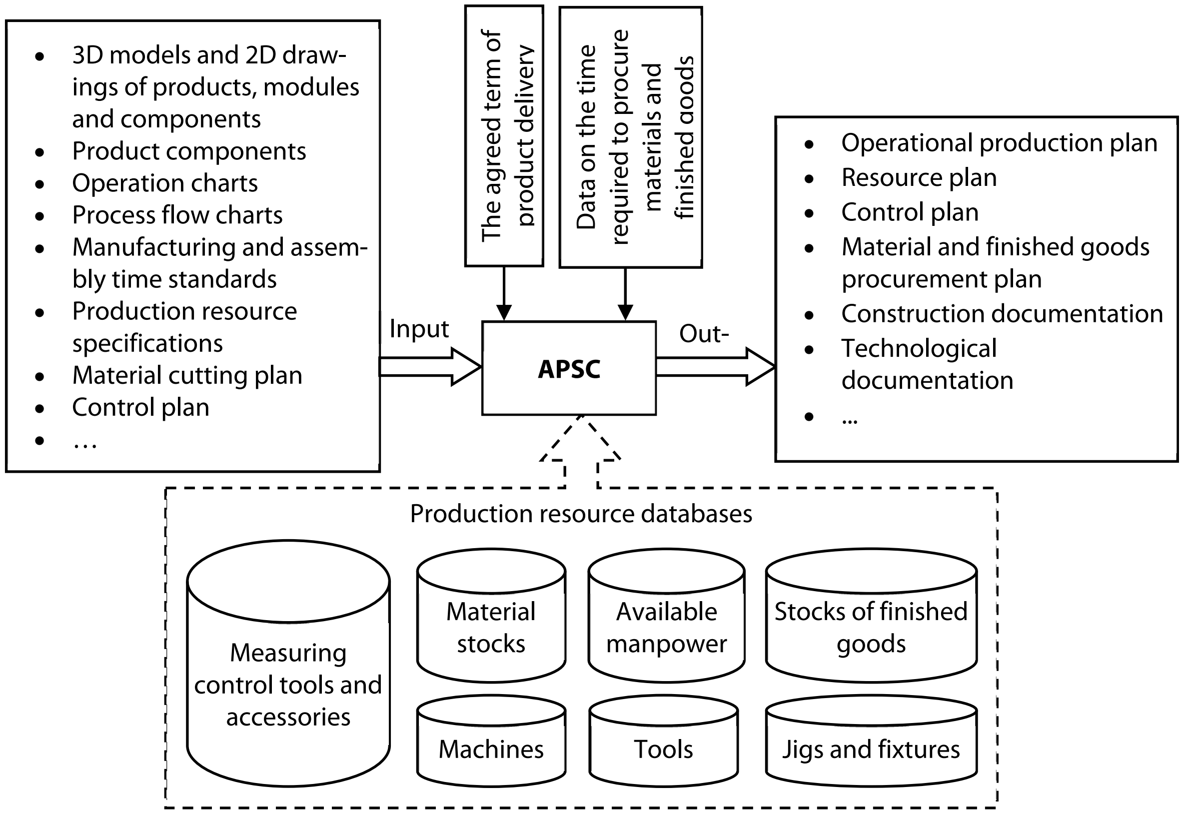


Figure 5: The structure of module 5: Advanced Planning and Scheduling Configurator [3]

The generation of an operational production plan necessitates the compilation of data from databases pertaining to available production resources, including machinery, tools, equipment, labor, measuring instruments, and materials in stock, among other elements. These resources constitute an integral component of the product platform (Module 9). In addition, the generation of an operational production plan requires the delivery date for the product, as well as data regarding the procurement time for materials and finished goods that are not currently in stock. Operational production planning is then executed based on the gathered information. The output from the module is comprised of several elements: an operational production plan, a resource plan, a control plan, a material and finished goods procurement plan, and documentation necessary for supplying production jobs. It should be noted that this documentation is forwarded to this module from modules 4 and 6.

3.6. Computer-Aided Design Product Configurator

The **Computer-Aided Design Product Configurator (CADPC)** is responsible for the automated conversion of the selected optimal product configuration into detailed 3D models, drawings, and BOM (Bill of Materials) using CAD systems. In this manner, accurate and thorough technical documentation is automatically obtained, including a virtual prototype of the product. This facilitates comprehension of the customized product for both the manufacturer and the customer. In the context of designing components and assemblies, contemporary CAD systems employ parametric design, a methodology that facilitates the management of product model geometry. Furthermore, these systems possess the capacity to integrate CAD with KBE and KBD methodologies, thereby facilitating the automation of the design process. This approach integrates geometry (CAD) with engineering knowledge, encompassing constraints, configuration rules, and algorithms. This facilitates the expeditious and effective generation of 3D CAD models based on specified parameters.

The **CADPC** structure is illustrated in Figure 6. This module utilizes the optimal configuration parameters (A^{opt}, p_k^{opt}) obtained from module 3 as input. It then designs (customizes) a product with the required characteristics in detail, based on constraints, rules, connections, and a 3D model database.

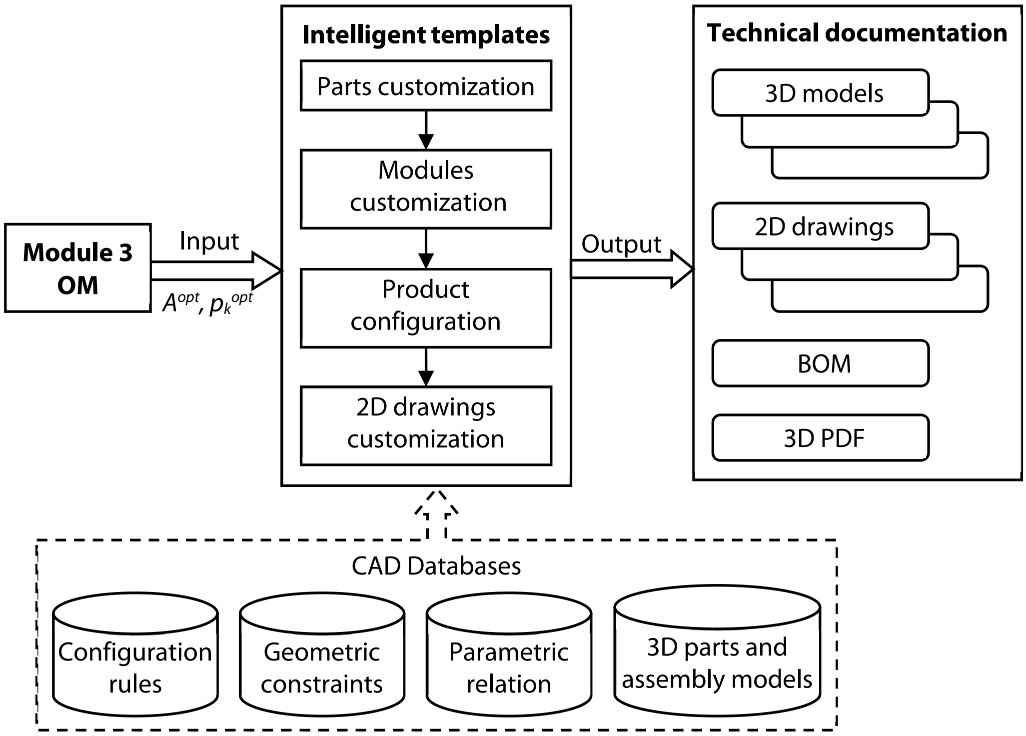


Figure 6: The structure of module 6: Computer-Aided Design Product Configurator [18]

The comprehensive configuration process entails the integration and customization of predefined 3D models of components, modules, and the entire product. All predefined parameters, constraints, connections, rules, and 3D models necessary for the configuration of a modular product are stored in CAD databases.

The output from this module comprises detailed 3D models and technical documentation of the product, all associated modules and components, as well as the material specification and the finished goods specification. It is noteworthy that these output data also function as the input data for modules 5 and 7. A thorough exposition of the design and operation of CADPC can be found in [18].

3.7. Sales Configurator

The **sales configurator (SC)** is responsible for preparing an offer for the customer, which is based on information received from modules 4, 5, and 6, as well as pricing information. The input data in the SC are as follows:

- operational production plan;
- construction documentation;
- technological documentation;
- supporting documentation about the product.

In accordance with the price data pertaining to materials, processing and assembly, finished goods, consumables, and additional materials, the sales configurator generates the following documentation for the customer:

- quotation;
- a covering letter;
- a product and service price specification;
- payment terms;
- a product delivery date;
- drawings, sketches, and product characteristics;
- additional documentation.

The structural diagram of the sales configurator is illustrated in Figure 7.

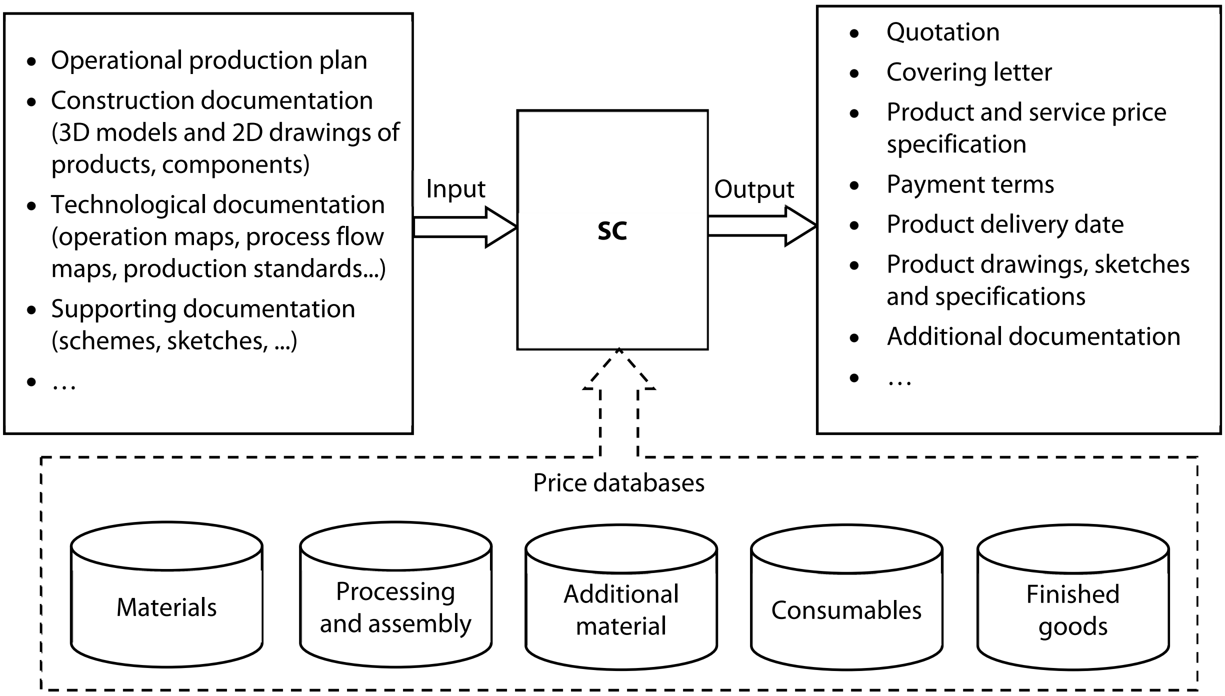


Figure 7: The structure of module 7: Sales Configurator [3]

The quotation, along with other pertinent documentation, is then forwarded to the customer via the GUI. In this interface, the customer can view a virtual representation of the product and access information regarding the price, deadline, delivery terms, and other relevant details. This enables the customer to confirm whether they wish to proceed with the purchase of the proposed product.

3.8. External Interface

The **external interface** facilitates automated exchange of information between all modules with the product platform and production system, as well as with other components of the business system (purchasing, sales, finance, etc.).

3.9. Product Platform

The fundamental prerequisite for the development of a family of configurable products is the existence of a common product platform. In this paper, the product platform is regarded in the most extensive sense, encompassing a series of modules, submodules, and product components, along with interfaces for their integration, a set of requirements and constraints, configuration rules, technologies, processes, human and technical resources, databases, knowledge bases, and other elements. This comprehensive framework facilitates the expeditious and efficient development of product variants that meet CRs. The proposed system is comprised of modules that are interconnected with the product platform via an external interface. These modules draw from the platform the knowledge and data necessary for configuring the optimal product variant, which, in turn, meets the individual CRs.

The initial development of an automatic MSR configuration platform was undertaken to achieve the automatic generation of an MSR variant, characterized by a fixed width for the standard product modules [4]. Subsequent enhancements to the platform were made with the objective of generating all possible MSR configuration variants. Consequently, the selection of the optimal configuration, characterized by the ideal width of each product module, can be accomplished through the implementation of multi-criteria decision-making methodologies. The improved platform and algorithm for generating all MSR variants are presented in the paper [15].

4. IMPLEMENTATION AND CASE STUDY

The implementation of the proposed system was carried out using the MSR type MODULPRIM (see Figure 8). MRS MODULPRIM is a component of the production program from "Primat" D.D. in Maribor, Slovenia, manufactured by Primat Equipment Ltd. in Baljevac, Serbia, and has been selected for IAKS MODULPRIM practical verification.

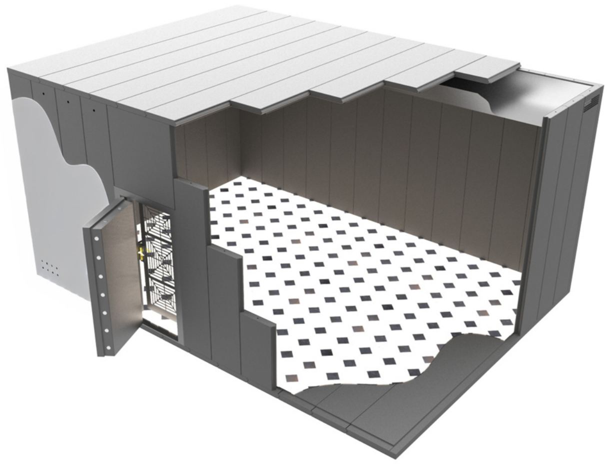


Figure 8: MSR MODULPRIM [4]

A total of eight examples of MSR MODULPRIM of resistance grade 5 of rectangular shape were selected to verify and validate the proposed system [13]. The examples were selected to represent the MSRs that are most often implemented. The dimensional parameters of the MSR in the selected examples range from A=2050÷9500 mm, B=2150÷8640 mm, and C=2500÷2910 mm. It is noteworthy that all the aforementioned examples were previously configured using the platform [4] and implemented in practice. The following table presents the fundamental dimensions of the MSR for the eight selected examples.

Table 1: Basic dimensions of MSR MODULPRIM 5 for selected examples

Dimension	Example							
	1	2	3	4	5	6	7	8
A [mm] - MSR length	9500	2050	3560	2200	2830	2350	4430	2900
B [mm] - MSR width	2800	3890	2150	3600	3590	3975	2150	8460
C [mm] - MSR height	2900	2910	2500	2500	2560	2540	2680	2800
D [mm] - Distance door to the left wall	4650	400	1860	506	705	575	2793	400
E [mm] - door width	1200	1150	1200	1104	1200	1200	1137	1200
F [mm] - door height	2110	2110	2105	2110	2165	2155	2110	2150

The initial step in utilizing IAKS MODULPRIM entails the entry of CRs into the GUI. GUI was developed using the MATLAB software environment and is depicted in Figure 9. The proposed scheme is comprised of two drop-down lists, one for selecting the resistance grade and another for indicating the direction of door opening. In addition, there are six fields designated for entering the basic dimensions of the MSR and strongroom door position. Finally, the scheme includes a sketch to facilitate understanding of the basic dimensions. Adjacent to these options is the "Configuration" button, which initiates the automated configuration process, and the "Offer" button, which generates a customer offer [13].

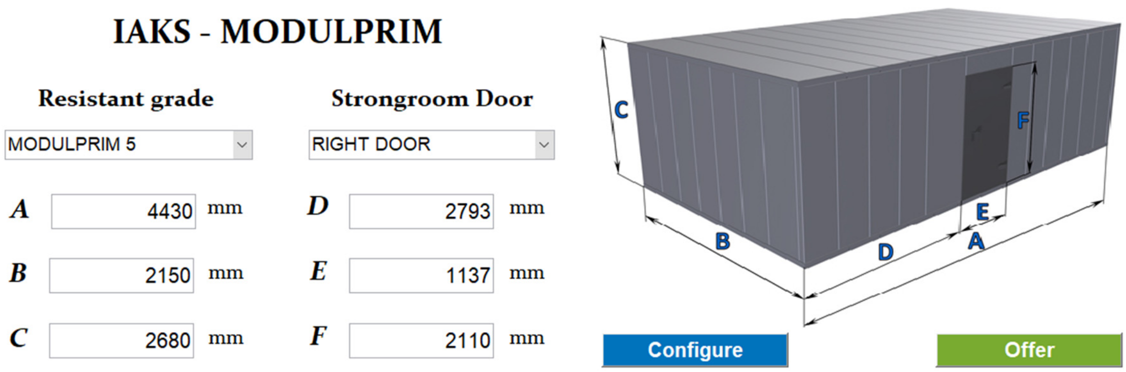


Figure 9: GUI layout with input data for example 7 [13]

Due to the geometric and technological similarity exhibited by these modules, they are divided into two groups: MSR wall forming modules and MSR floor/ceiling forming modules [3]. Consequently, the comprehensive process of generating alternatives and selecting the optimal configuration is executed twice, particularly for walls and floor/ceiling MSR. The MSR conceptual configurator was utilized to generate all feasible MSR configurations, accompanied by all pertinent parameters, for the selected examples. As delineated in Table 2, the aggregate number of alternatives for each example is exhibited, separately for walls and floor/ceiling.

Table 2: Total number of alternatives for all examples

Example	1	2	3	4	5	6	7	8
Wall alternatives	164	260	213	267	281	274	237	276
Floor/ceiling alterantives	347	340	305	311	309	103	362	328

Given the nature of the problem, a solution was devised through the integration of Analytical Hierarchy Process (AHP) methodologies and Simple Additive Weighting (SAW) techniques from the Multiple Attributes Decision Making (MADM) group. To ensure an objective allocation of weighting factors, the AHP method was implemented. This method was chosen to avoid the subjective assignment of weights by the decision-makers. Conversely, the problem comprises numerous alternatives whose performance can be quantified numerically. Consequently, the selection of the SAW method to identify the optimal alternative was a rational choice [13].

The paper [13] provides a thorough description and algorithms for implementing AHP and SAW methods, as well as a description of the operation of the optimization module. As delineated in Table 3, the optimal configuration is determined by the implementation of four distinct criteria functions. Furthermore, the process of verification and validation of the optimization module is delineated, which integrates the following: 1. Defining the Objective and Problems of Decision-Making; 2. Structuring the Problem; 3. Relative Weights of Criterion Functions; 4. Choosing an Optimal Alternative.

Table 3: Criteria functions [3, 13, 19]

Criteria	Criteria description	Function
C_1	Total production and assembly time of MSR	$T_{tot} = \sum_{i=1}^{m} T_{tot_i} = T_{cut} + T_{ben} + T_{ma} + T_{cc} + T_{dp} + T_{pal} + T_{pac} + T_{ass}$ [h]
C_2	Total MSR production costs	$C_{tot} = C_{mat} + C_{work} = \sum_{i=1}^{n} C_{mat_i} + \sum_{j=1}^{k} C_{work_j}$ [€]
C_3	Total number of defects in all modules	$G_{tot} = \sum_{i=1}^{8} G_i \cdot N_i$
C_4	Sum of maximum deviations from the flatness of the surfaces of all modules	$R_{tot} = \sum_{i=1}^{8} R_{max\,i} \cdot N_i$

The AHP method was employed to estimate the relative weights of the criteria, as illustrated in Table 4.

Table 4: Relative weights of criteria

Criteria	$C_1 = \min T_{UK}$	$C_2 = \min C_{UK}$	$C_3 = \min G_{UK}$	$C_4 = \min R_{UK}$
Wj	0.0981	0.6644	0.0559	0.1815

The complete procedure for calculating the criterion functions for each alternative, as well as the optimization process itself, were carried out in MATLAB and are presented in the publications [3, 13]. The application of IAKS MODULPRIM for selecting the optimal configuration will be demonstrated below for a single example (No. 7). The diagrams illustrating the aggregate objective function, along with the position of the optimal alternatives in relation to the derived solutions for example 7, are presented in Figure 10.

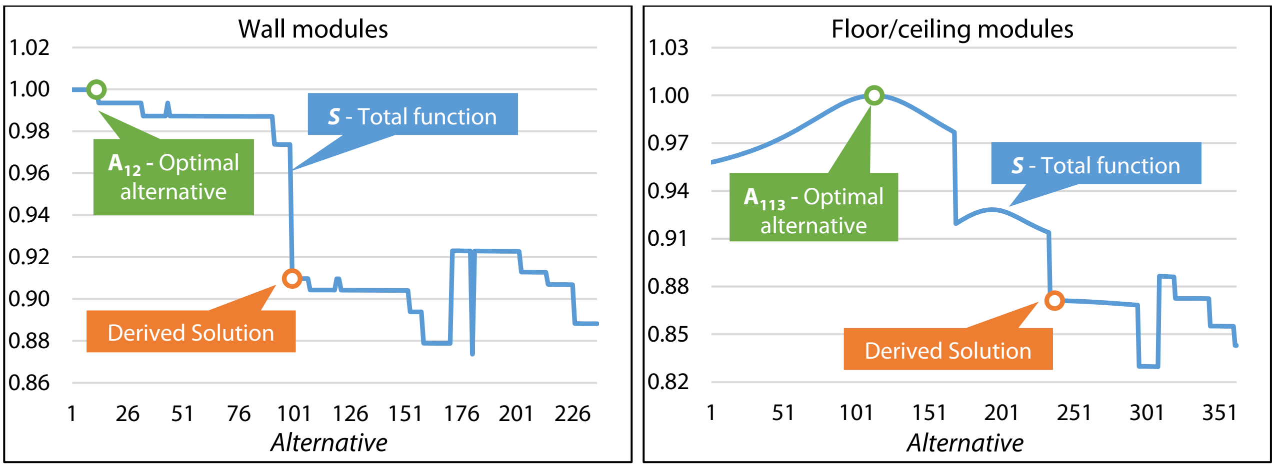


Figure 10: Summary objective functions with the position of optimal alternatives in relation to the derived solutions

In the subsequent phase, the MSR design undergoes automatic customization in Autodesk Inventor, guided by the parameters of the optimal alternative. The integration was executed through the utilization of the iLogic software, within which the rules that automate the design process were formulated. The rules have been formulated in accordance with the MSR configuration platform.

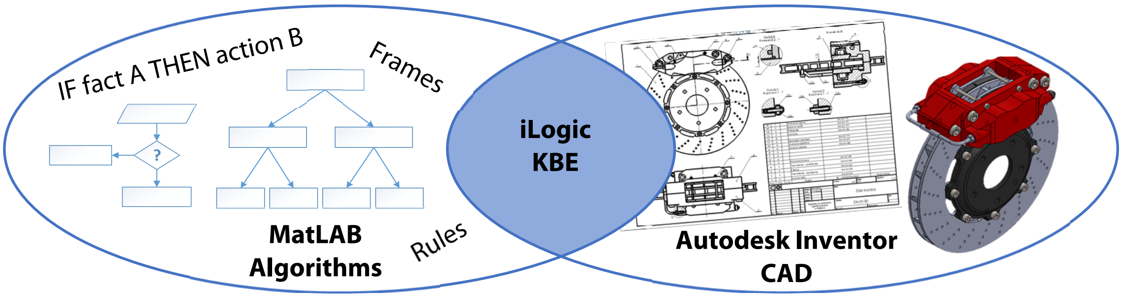


Figure 11: Integration of CAD with algorithms (frames, constraints, design rules, etc.)

The configuration of the MSR is dependent on the automatic configuration of all 3D components and 3D assemblies necessary to form the modules. For configuring example 7, a total of 29 modules (8 different modules) are required to configure the MRS, which is shown in Figure 12 (left). Furthermore, the technical drawings for all components that require fabrication, in addition to the assembly drawings of all modules and the entire MRS, have been revised. As illustrated in Figure 12 (right), a one technical drawing is provided for a component that must be fabricated.

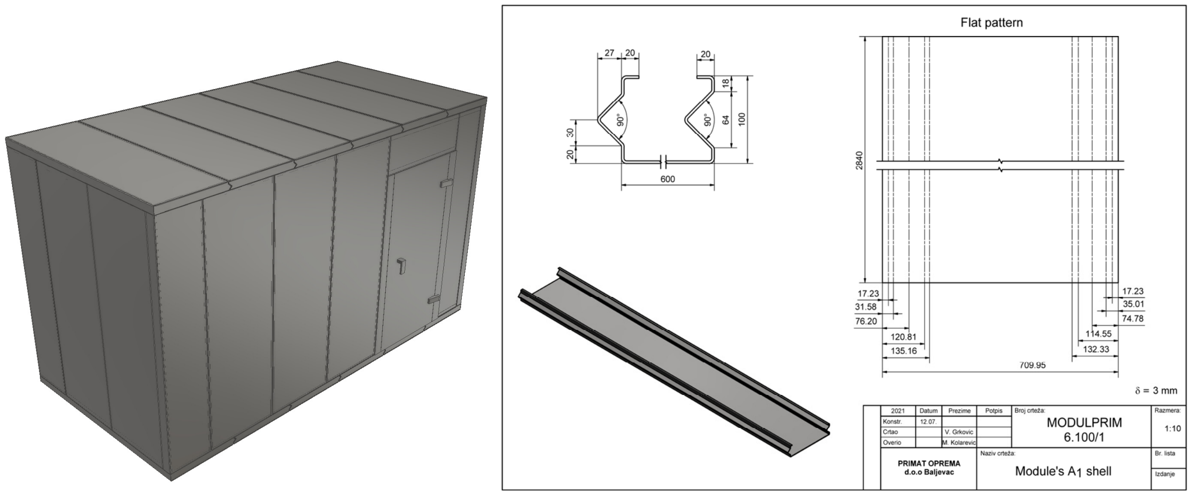


Figure 12: Custom 3D model of the MSR (left) and technical drawing of the A1 module shell (right)

In determining the delivery date, IAKS MODULPRIM automatically generates a Gantt chart, which visually displays the key activities, their implementation times, and resources (Figure 13).

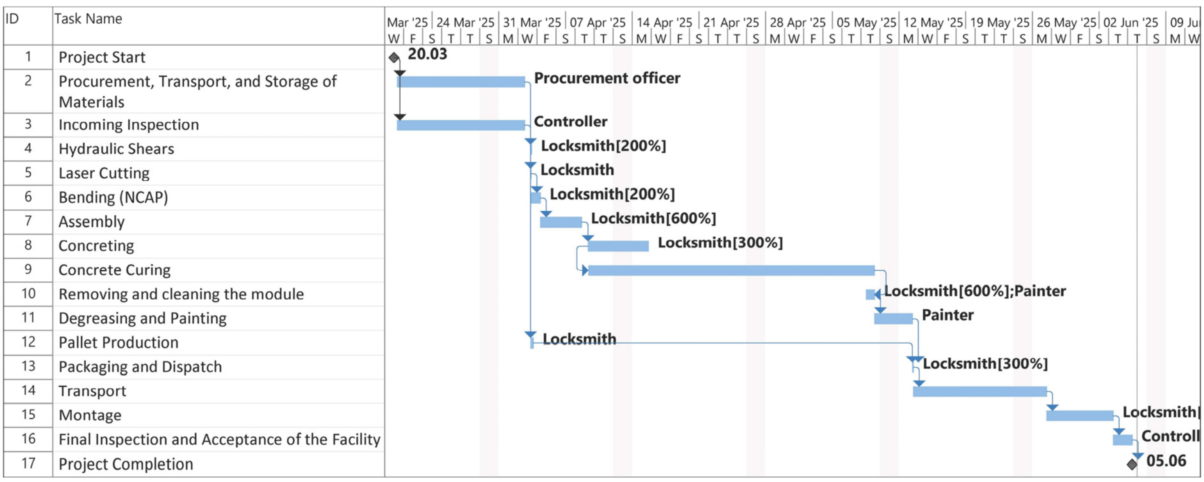


Figure 13: Automatically generated Gantt Chart for Example #7

To automate the proposed system, the main program code was written in MATLAB. Its primary function is to establish interconnections among all modules. This entails receiving CRs from the GUI and, further, in a certain order, forwarding them to other modules requesting defined feedback.

5. DISCUSSION AND RESULTS ANALYSIS

The application of an integrated system (IAKS MODULPRIM) enables the complete automation of the MSR configuration process. This approach has been shown to significantly reduce the time required for the design of the MSR and eliminate errors from the design process. The automatic selection of the optimal MSR configuration has been demonstrated to reduce subjectivity in decision-making processes.

A thorough analysis was conducted into the implementation of IAKS MODULPRIM across all eight case studies. The values of the criterion functions for the derived solutions (based on the old product platform) and the optimal solutions (selected based on IAKS MODULPRIM, based on the new product platform) were meticulously compared [3, 13]. The effects of the application are as follows:

- An average decrease of 3.3% in the total time required to produce and assemble the MSR;
- An average reduction of 7.0% in total production costs;
- An average 28.7% decrease in the total number of errors in all MSR modules; and
- An average reduction of 12.5% in the total sum of the maximum deviations from the flatness of the surfaces of all modules.

Furthermore, a reduction in the number of modules was observed, resulting in the following findings:

- For instance, in example 7, the number of distinct wall modules was diminished by 2 modules (19%), and the total number of modules was reduced by 7 modules (20%);
- For all 8 examples, the number of different modules on the walls is lower due to the reduction of the number of non-standard modules by an average of 11.11%, which contributes to the rationalization of production;
- For all 8 examples, the total number of modules necessary to produce one MSR was reduced by an average of 18.32% for walls and by 25% for floors/ceilings. This reduction is also suitable for the rationalization of production.

6. CONCLUSION

The development of the MSR platform engendered the possibility the generating numerous feasible alternatives for the same CRs, thereby necessitating the selection of the optimal solution. The present study puts forth a proposal for an integrated automatic configuration system for MSR (IAKS MODULPRIM). This system combines key elements in the development of modular products, including multi-attribute decision making and CAD tools. IAKS MODULPRIM facilitates the generation of all MSR configurations, the selection of the optimal MSR configuration, the CAD design of the MSR (in the form of 3D models and technical documentation), the creation of technological documentation, and the creation of a quote for the customer.

The integration of these methodologies has been demonstrated to yield several benefits, including enhanced efficiency and accuracy in MSR design, a reduction in production time and costs, and an improvement in MSR quality. A case study involving the implementation of IAKS MODULPRIM in eight real-world scenarios demonstrated a cumulative improvement effect of **10.3%.**

The automation of the product configuration process has enhanced the efficiency of the system by reducing or eliminating repetitive tasks and decreasing design time. It is possible to swiftly provide the customer with the desired MSR configuration of exceptional quality at the lowest possible price in the shortest possible time.

The software implementation of the complete system was executed in MATLAB, Autodesk Inventor, iLogic, and MS Project. Future research endeavors aimed at enhancing IAKS MODULPRIM might encompass the following directions:

- Verification and validation on new examples;
- Inclusion of new criterion functions and optimization algorithms;
- Application of artificial intelligence methods; and
- Identification of real practical challenges in implementation in the company's business system.

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