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CONCEPTUAL CONFIGURATOR OF MODULAR STRONGROOMS

Vladan Grković, Milan Kolarević, Aleksandra Petrović, Mišo Bjelić, Stefan Pajović
University of Kragujevac, Faculty of Mechanical and Civil Engineering, Kraljevo, Republic of Serbia

Abstract: *To compete on current market, it is necessary to quickly respond to customer requirements (CRs) and enable customers to choose the product that suits them. Complex products, such as Modular strongrooms (MSR), often meet customer requirements with several different configurations, so it is important to choose the optimal product configuration. For this purpose, in the past decade, a model of integration automatic configuration system (IAKS MODULPRIM) has been developed. IAKS MODULPRIM automatically generates all possible product configurations that meet customer requirements, select the optimal configuration based on time, cost and quality and designs in detail the product and technological procedures.*
The conceptual product configurator is part of IAKS MODULPRIM which task is to automatically generate all possible configurations based on new developed product platform and customer requirements. Output of the conceptual product configurator allows the IAKS MODULPRIM to properly rank and select the optimal configuration based on predefined criteria.

Key Words: ***Conceptual Product Configurator, Modular Strongrooms, IAKS MODULPRIM, Product Platform***

1. INTRODUCTION

The dominance of customer requirements in the modern market requires manufacturers to be flexible in product design, to respond quickly to customer requirements (CRs) and to be able to develop products according to individual customer requirements. The Mass customization (MC) strategy offers: 1) efficient solutions for customer involvement in the product creation process, 2) new product configuration methods based on architecture, platforms and product configurators, and 3) development of efficient production customization solutions.

One of the main directions for supporting the MC paradigm is the development and application of product configuration systems (PCSs), also known as product configurators [1–3].

Product Configurator is a computer tool based on expert systems (ES) or knowledge-based systems (KBS) that allows customization of the product by implementing the process of product configuration [4–6]. The role of the product configurator is to quickly bridge the gap between CRs and the final product [7], i.e. to provide support to customers (required amount of information) in the process of collecting their requests and to adequately transform CRs into correct and feasible product specifications or modules [8].

Product configurators are used in various industries and their application provides significant advantages [9–12]:

- the possibility of fulfilling a number of CRs,
- successful implementation of MC,
- shortening the time of product appearance on the market,
- reduction of costs,
- a greater variety of products is offered,
- shorter delivery cycles of the product variant,
- users are integrated into the design process, etc.

Configurable products usually use a modular architecture where the product is decomposed into functional modules whose selection and combination can be used to configure different product variants within the product family [13]. The development of configurable products is based on a product platform that represents a set of subsystems (components, modules or parts) and interfaces that form a common structure from which product variants can be efficiently developed and produced [14,15].

Modular strongrooms (MSR) are complex, technically and technologically demanding products. They are designed at the individual CRs, who chooses the resistance grade of the room according to EN 1143-1 and defines dimensions of the available space to fit required product [16–18].

The MSR architecture is modular and the configuration is accomplished by a combination of standard modules whose number and dimensions must be adjusted in each new project.

With complex products, such as MSR, CRs can be satisfied with a number of different configurations, with the problem of choosing the optimal configuration. The solution was found in the development of Integration automatic configuration system - IAKS MODULPRIM [19] which automatically generates all feasible product configurations that meet CRs, selects the optimal configuration based on time, cost and quality criteria and designs the product in detail.

The conceptual product configurator is part of IAKS MODULPRIM and has the task to automatically generate all possible configurations based on the developed product platform and CRs. Based on the predefined criteria, the optimal configuration of the MSR is selected in the further procedure [19]. Furthermore, for optimal configuration, the 3D model is automatically designed / adjusted using the CAD configurator [18].

An improved configuration platform for MSRs is discussed in Chapter 2 and a general model of conceptual configurator based on the new platform is presented in Chapter 3. The effects of the implementation are given in Chapter 4 and the main advantages of the proposed approach in conclusion (Chapter 5).

2. NEW PLATFORM FOR AUTOMATIC CONFIGURATION OF MSR

The previous MSR Automatic Configuration Product Platform [17] defines: set of requirements and constraints, set of modules, submodules and components, module connection rules, calculation of module parameters and MSR configuration rules. The previous platform is designed to configure only one variant of MSR based on CRs. A fixed width of standard modules **A** and **D** (550mm) was used and fitting into the required dimensions of the available space was performed by adjusting the dimensions of non-standard modules.

In order to integrate product design, production processes and adaptation to production conditions, the following changes were adopted:

- Non-standard modules **A2**, **A3** and **A4** have been eliminated from the MSR configuration, thus reducing the number of different modules.
- Instead of the fixed width of standard modules **A** and **D**, the optimal value of the width is calculated from the aspect of rationalization of time, production and assembly costs and achieving better quality in the MSR production process.

The shape and structure of the modules, the classification of the modules, their connections, the basic parameters of the modules, the resistance grade as well as the input data obtained from the customer (Figure 1) remain the same as in the previous platform [17].

2.1. Configuration procedure scheme

Reducing the number of different modules requires a new scheme of the MSR configuration procedure shown in Figure 2, and consists of the following steps:

1. Forming a floor from a modules **Cz**, **D** and **C**;
2. The front wall is formed of three areas: *a*) the area left to the MSR door consisting of modules **B1** and **A**, *b*) the central area consisting of the MSR door and module **E**, and *c*) the area right to the MSR door consisting of modules **A** and **A1**. The left side of the front wall is connected to the module **A** of the left side wall by module **B1** and the right side of the front wall is connected to the module **B2** of the right side wall by module **A1**. The entire length of the front wall is connected to all floor modules.
3. The right side wall is formed by modules **B2** and **A**. It is connected to the front and back wall by modules **B2** and **B3**, and it is connected to the floor by module **C**.
4. The back wall is formed of modules **B3** and **A**. It is connected to the side walls by modules **B3** and **B2** and is connected to all floor modules for the floor.
5. The left side wall is identical to the right side wall. It is connected to the front and back walls by modules **B1** and **B2**, and it is connected to the floor by module **Cz**.
6. The ceiling is formed from the same modules as the floor: **Cz**, **D** and **C** and it is connected to all the modules from which the MSR walls are made.

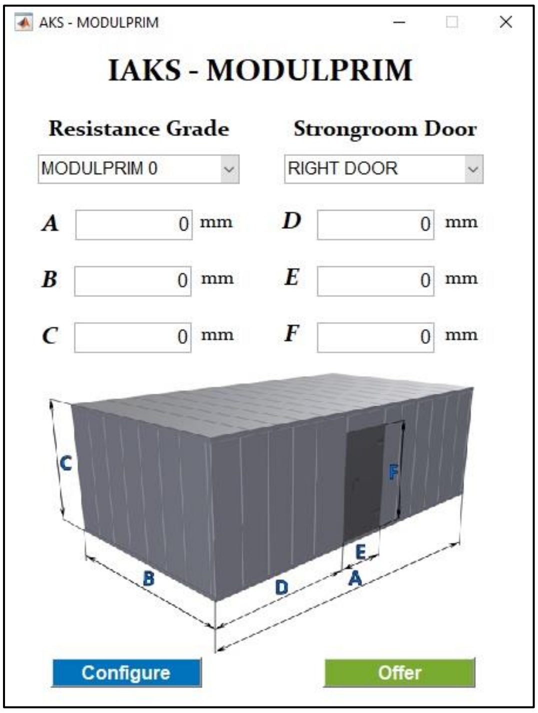

Fig. 1. *Graphical user interface* [19]

2.2. Calculation of module parameters

To generate possible MSR configurations, the calculation of basic parameters of each module as well as the structure definition of the complete MSR, based on new platform is required. The adopted calculation of each MSR side is shown below.

1) Calculation of front wall module parameters

The basic parameters of the front wall and the structure of the module of which the front wall consists are shown in Figure 3.

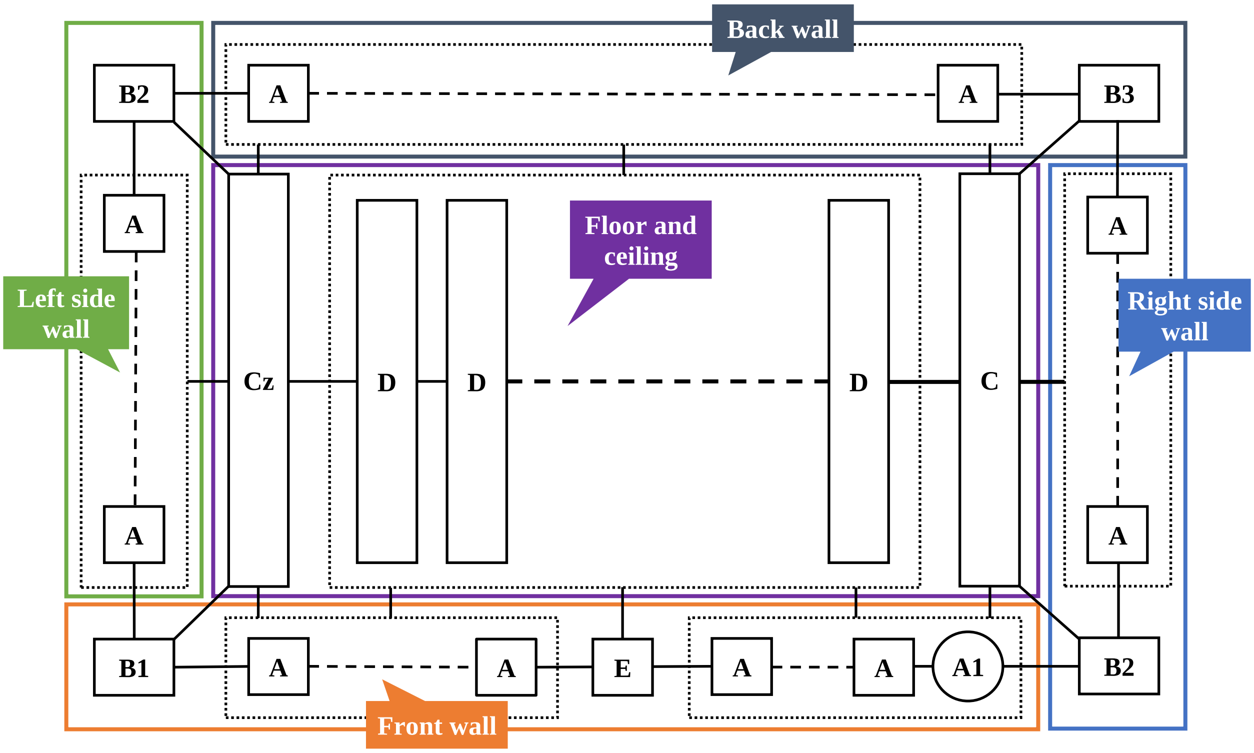

Fig. 2. *The developed scheme of the MSR configuration procedure*

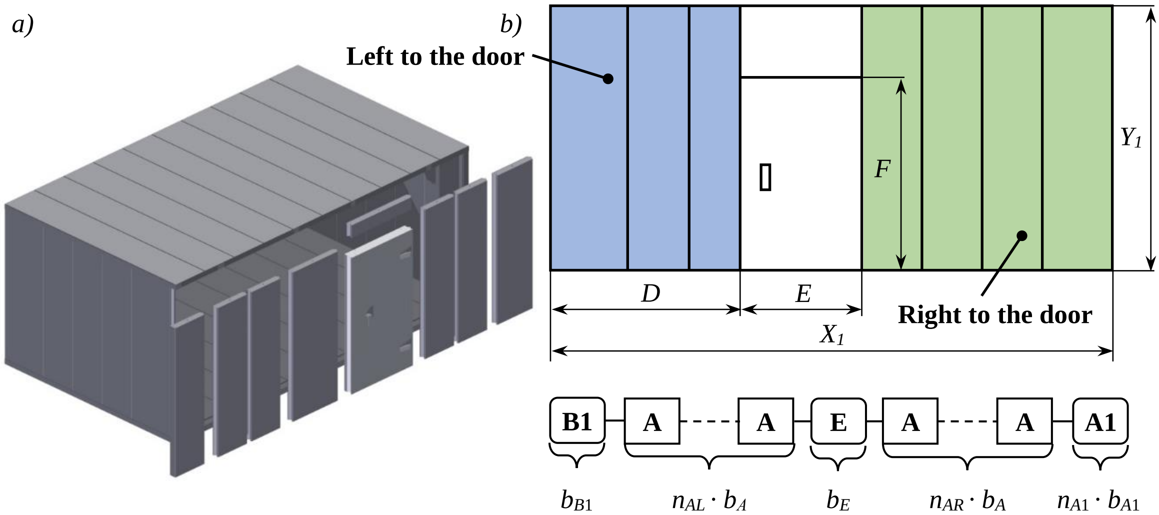

Fig. 3. *a) 3D view of the disassembled MSR front wall; b) MSR front wall structure and parameters*

Some of the front wall parameters are obtained directly from the CRs (E, F, D and d), while other parameters need to be calculated. Expressions and constraints are:

$$X_1 = A - d\,, \tag{1}$$

$$Y_1 = C - 2\cdot\left(d - d_p\right), \tag{2}$$

$$b_E = E\,, \tag{3}$$

$$l_E = Y_1 - F\,, \tag{4}$$

$$D + E + n_{AR}\cdot b_A + n_{A1}\cdot b_{A1} = A - d\,, \tag{5}$$

$$b_{B1} + n_{AL}\cdot b = D\,, \tag{6}$$

$$0 \le n_{A1} \le 1\,, \tag{7}$$

$$n_{B1} = 1\,, \tag{8}$$

where: X_1- front and back wall length, Y_1 - all walls height, b_A - module **A** width, b_{A1} - module **A1** width, b_{B1} - module **B1** width, n_{AL} - number of modules type **A** on the left side to the door and module **E**, n_{AR} - number of modules type **A** on the right side to the door and module **E**, n_A - number of modules type **A1**, n_{B1} - number of modules type **B1**, b_E - module **E** width, l_E - module **E** length.

2) Calculation of side wall module parameters

As both side walls (left and right) are identical, i.e. consist of the same modules, the calculation is shown for the right wall only. The basic parameters of the side wall and the structure of the modules of which it consists are shown in Figure 4.

Parameter calculation is performed using the following expressions and constraints:

$$X_2 = B - d\,, \tag{9}$$

$$n_{B2} = 1, \quad (10)$$

$$b_{B2} + n_{AS} \cdot b = B - d, \quad (11)$$

where: X_2 - the length of one side wall, b_{B2} - module width **B2**, n_{AS} - number of modules **A** on one side wall, n_{B2} - number of modules **B2**.

3) Calculation of back wall module parameters

The basic parameters of the back wall and the structure of the modules of which it consists are shown in Figure 5.

Basic dimensions of the back wall (X_1 and Y_1) are determined in the same way as for the front wall (equations 1 and 2). Parameter calculation is performed using the following expressions and constraints:

$$b_{B3} + n_{AB} \cdot b_A = A - d, \quad (12)$$

$$n_{B3} = 1, \quad (13)$$

where: b_{B3} - module width **B3**, n_{AB} - number of modules **A** on one back wall, n_{B3} - number of modules **B3**.

4) Calculation of floor and ceiling module parameters

As the structure of the floor and ceiling is identical, i.e. they consist of the same modules, the calculation is shown for the ceiling only. The basic dimensions and structure of the modules of which the ceiling consists are shown in Figure 6.

For floor and ceiling modules, there is a rule that the modules are placed in the direction of the shorter MSR wall. Parameter calculation is performed using the following expressions and constraints:

$$X_3 = \begin{cases} B; \text{ IF}(B \le A \text{ and } A \le C_{\max}) \\ A; \text{ IF}(B \le A) \text{ or IF}(A < B \text{ и } B \le C_{\max}) \\ B; \text{ in other cases} \end{cases}, \quad (14)$$

$$Y_2 = \begin{cases} A; \text{ IF}(B \le A \text{ and } A \le C_{\max}) \\ B; \text{ IF}(B \le A) \text{ or IF}(A < B \text{ и } B \le C_{\max}) \\ A; \text{ in other cases} \end{cases}, \quad (15)$$

$$n_C = n_{Cz} = 1, \quad (16)$$

$$X_3 = b_C + n_D \cdot b_D + b_{Cz}, \quad (17)$$

where: b_D - standard module width **D**, b_C - module width **C**, b_{Cz} - module width **Cz**, n_D - number of modules **D** on the ceiling (the same number is on the floor), n_C - number of modules **C**, n_{Cz} - number of modules **Cz**, X_3 - ceiling length and Y_2 - ceiling width.

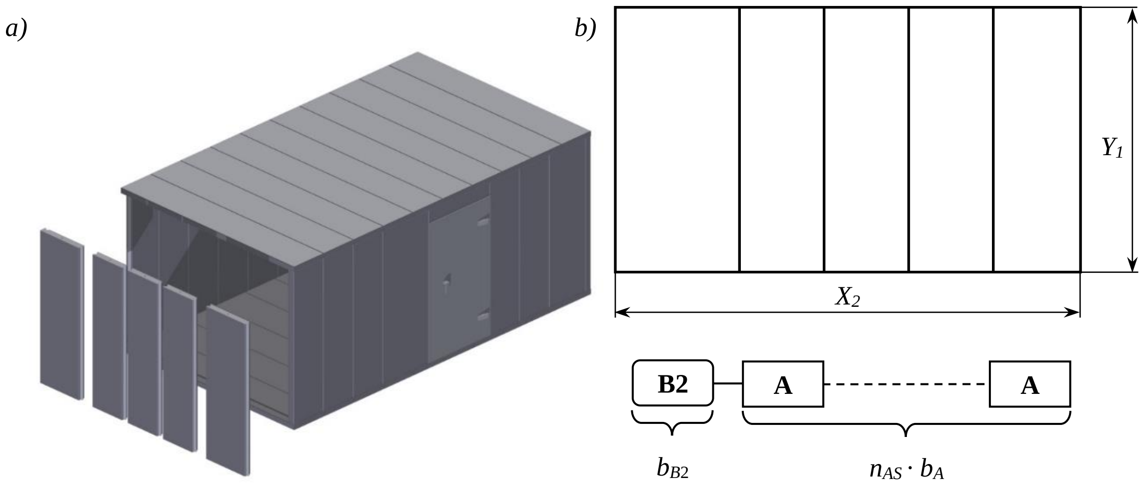

Fig. 4. *a) 3D view of the disassembled MSR side wall; b) MSR side wall structure and parameters*

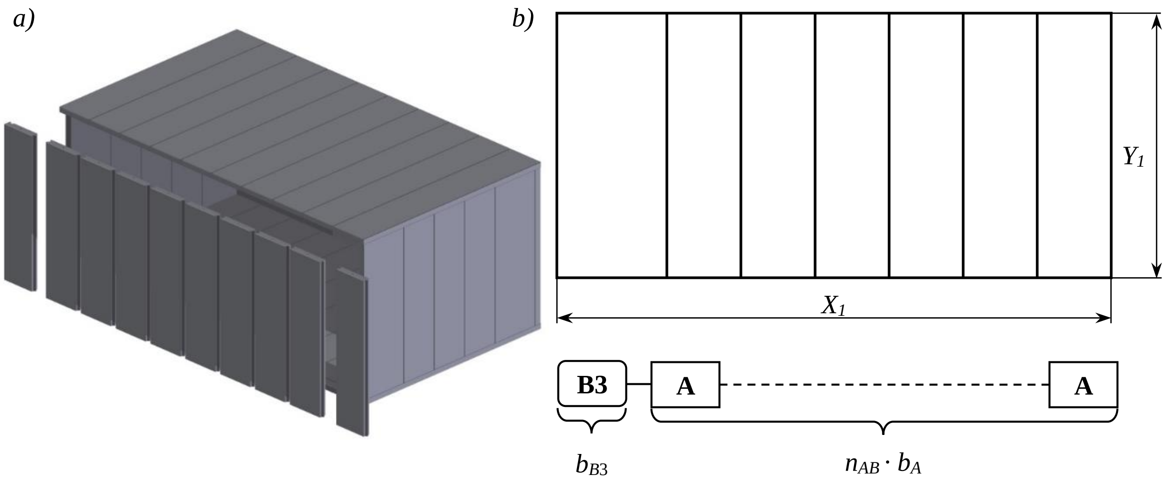

Fig. 5. *a) 3D view of the disassembled MSR back wall; b) MSR back wall structure and parameters*

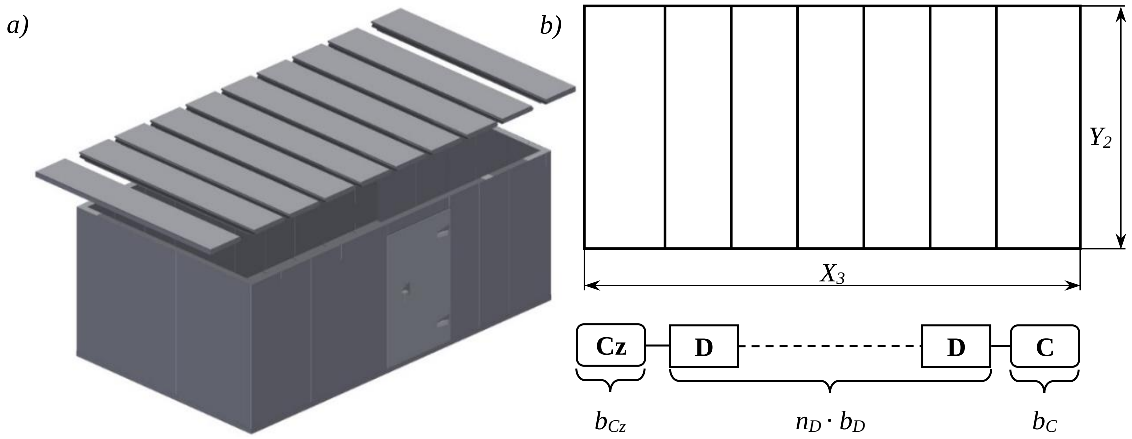

Fig. 6. *a) 3D view of the disassembled MSR ceiling; b) MSR ceiling structure and parameters*

2.3. Technology constraints

Technological constraints define that the width of each module must be in the range of 400 mm ($b_{\min}$) to 850 mm ($b_{\max}$) and that is an integer. The maximum module length is 6000 mm ($l_{\max}$), and the height of MSR is in the range of 2000 mm ($C_{\min}$) to 2950 mm ($C_{\max}$).

$$b_{\min} \le b_{ij} \le b_{\max} , \quad (18)$$

$$b_{ij} = \mathrm{int}\left[\mathrm{mm}\right], \quad (19)$$

$$l_{ij} \le l_{\max} , \quad (20)$$

$$l_A = l_{A1} = l_{B1} = l_{B2} = l_{B3} = Y_1 , \quad (21)$$

$$l_D = l_C = l_{Cz} = Y_2 , \quad (22)$$

$$C_{\min} \le C \le C_{\max} , \quad (23)$$

$$n_{ij} = \mathrm{int} , \quad (24)$$

$$n_{ij} \ge 0 , \quad (25)$$

where: l_A, l_{A1}, l_{B1}, l_{B2}, l_{B3} – lengths of wall modules **A**, **A1**, **B1**, **B2**, **B3**, l_D, l_C, l_{Cz} – length of floor/ceiling modules **D**, **C** i **Cz**, C – height MSR.

2.4. MSR assembly parameters calculation

As there are two identical side walls, as well as an identical floor and ceiling, the module numbers from which these building blocks are formed must be duplicated. Module **A** is located on all walls, so the total number is obtained as the sum of the number of modules needed to form each wall. The total module numbers required to configure the MSR are:

$$N_A = n_{AL} + n_{AR} + 2 \cdot n_{AS} + n_{AB} , \quad (26)$$

$$N_{A1} = n_{A1} , \quad (27)$$

$$N_{B1} = n_{B1} , \quad (28)$$

$$N_{B2} = 2 \cdot n_{B2} , \quad (29)$$

$$N_{B3} = n_{B3} , \quad (30)$$

$$N_C = 2 \cdot n_C , \quad (31)$$

$$N_{Cz} = 2 \cdot n_{Cz} , \quad (32)$$

$$N_D = 2 \cdot n_D , \quad (33)$$

$$N_E = n_E , \quad (34)$$

where: N_A - total number of modules **A**, N_{A1} - total number of modules **A1**, N_{B1} - total number of modules **B1**, N_{B2} - total number of modules **B2**, N_{B3} - total number of modules **B3**, N_C - total number of modules **C**, N_{Cz} total number of modules **Cz**, N_D - total number of modules **D** and N_E - total number of modules **E**.

3. CONCEPTUAL PRODUCT CONFIGURATOR

The conceptual product configurator has the task of automatically generating possible product configuration variants based on CRs. The structure of the conceptual configurator is shown in Figure 7. It consists of converters, generators of feasible product configurations and databases.

The converter transforms order data (CRs) into technical data used to configure the product. With configurators, certain CRs are often defined by selecting specific text from the options offered within a drop-down list or checklist. The selected text is mostly not usable in that form, so it needs to be translated into another form (usually numerical).

As an example with MSR, the choice of door orientation and resistance grade from the drop-down list can be mentioned. Based on the choice of door orientation (left or right), the direction of MSR configuration is determined (Figure 1). The converter transforms the text selection into numeric data, which the generator will understand and further process.

The resistance grade is also selected from the drop-down list and it is possible to choose grades from 0 to XIII. For each resistance grade, the standard prescribes the wall thickness MSR (d), and thus the module thickness, so the value of the parameter d is obtained by converting the selected degree of resistance into a numerical value of the module thickness.

Generator of feasible product configurations has the task of configuring all possible conceptual product variants that meet individual CRs based on the product configuring rules, product database, modules and components, respecting the defined constraints. Rules database, modules and constraints are created based on the product platform.

The output from the conceptual product configurator is the specification of configuration variants, which includes the structural parameters of the product as well as the basic parameters of modules, components, materials, etc. From this specification, IAKS MODULPRIM selects the optimal configuration and designs the product in detail.

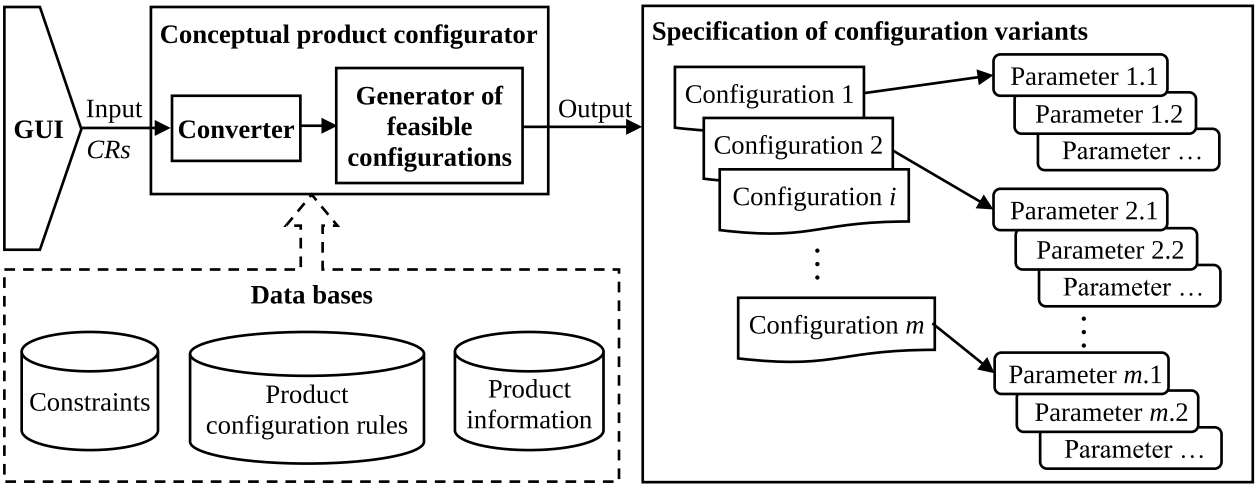

Fig. 7. *The structure of the conceptual product configurator*

Based on the presented configuration scheme (Figure 2) and product constraints, presented within the new MSR configuration platform, an algorithm was developed to calculate and generate possible configuration variants for all walls, floor and ceiling. The configuration of the MSR is performed according to the pseudo code shown in algorithm 1. Below is a brief explanation of the algorithm.

Algorithm 1. *Pseudo code of the conceptual product configurator*

```
input CRs to GUI
convert CRs
for i=1:s    //generating configurations variants
   for j=1:(bmax-bmin+1)  // for all wall/floor variants
      generating a standard module width bij=bmax-j+1
      calculation of structure parameters
      calculation of basic modules parameters
      if it is a feasible variant?
         save all parameters for variant
      else
         delete variant
      end if
   next j    //next variant
   end for
next i    //next building blocks
end for
```

The algorithm starts by entering CRs in the GUI (Graphical User Interface) and converting CRs. After that, configurations for each wall (including floor and ceiling) are generated. It calculates all parameters, checks the feasibility of the configuration and records the correct configurations.

As the MSR consists of a front wall, side walls, back wall, floor and ceiling, it is necessary to generate configurations for 4 times (s = 4).

In order to determine the optimal width of the standard module (for walls it is module **A** and for floor/ceiling module **D**) all values in the range of b_{min} to b_{max} in increments of 1 mm are being examined (to obtain integer values in mm). The maximum number of technically feasible variants for each wall is obtained using the expression $j=b_{max}-b_{min}+1$, which amounts to 451 in this case. The same maximum number of variants can be generated for the floor/ceiling.

4. APPLICATION EFFECTS

Validation of IAKS MODULPRIM was performed on 8 examples of MSR MODULPRIM resistance grade 5. The parameters of MSR for the mentioned examples can be found in [19].

The examples were selected to represent the most commonly implemented MSRs. The basic dimensions of the MSR from the examples are in the ranges: A=2050÷9500 mm, B=2150÷8640 mm and C=2500÷2910 mm. Most of the mentioned examples have been practically implemented in the past decade.

By generating variants for the mentioned examples, the solutions shown in Figure 8 were obtained. The solutions are presented by the numbers of possible variants for walls and for floor/ceiling.

An overview of the configuration variant specifications for Example 1 for wall modules is given in Table 1.

Effects of IAKS MODULPRIM validation based on the new platform and on the possibility to select the optimal from the final set of possible configurations are [19]:

- Total time to produce and assemble MSR is down 3.3% on average.
- Total production costs are reduced by an average of 7%.
- Total number of defects on all MSR modules are reduced by an average of 28.7%
- The total sum of the maximum deviations from the flatness of the surface of all modules is reduced by an average of 12.5%.

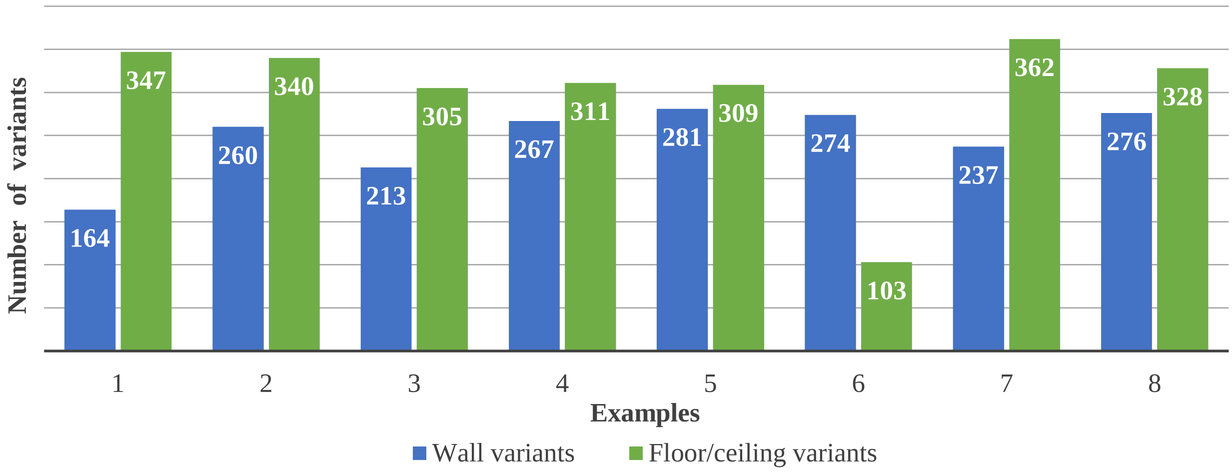

Fig. 8. *Total number of variants for all walls and floor/ceiling for all 8 examples*

Table 1. *Configuration variant specification parameters for example 1 for all walls*

Variants	Basic walls parameters									
	b	b_{A1}	b_{B1}	b_{B2}	b_{B3}	n_{AL}	n_{AR}	$2 \times n_{AS}$	n_{AB}	n_{A1}	N_A
1	692	782	498	624	404	6	4	6	13	1	29
2	691	786	504	627	417	6	4	6	13	1	29
3	690	790	510	630	430	6	4	6	13	1	29
4	689	794	516	633	443	6	4	6	13	1	29
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
161	403	729	620	685	534	10	7	10	22	1	49
162	402	736	630	690	556	10	7	10	22	1	49
163	401	743	640	695	578	10	7	10	22	1	49
164	400	750	650	700	600	10	7	10	22	1	49

5. CONCLUSION

Conceptual configurator of MSR was developed as part of the integrated automatic configuration system (IAKS MODULPRIM) developed at the Faculty of Mechanical and Civil Engineering in Kraljevo. Output of the system is optimal configuration variant of the product that meets the individual requirements of the customer and which is the most economic for the manufacturer.

The application of the new advanced MSR platform and the MSR conceptual configurator enables the IAKS MODULPRIM system to automatically obtain all parameters of feasible product configurations. Based on them, in the following phases, the optimal configuration is selected and the product is designed in detail (with the help of a CAD configurator).

This paper is another example that the development of product configuration systems is the basic way to achieve the paradigm of mass customization and ensure competitiveness in the modern market.

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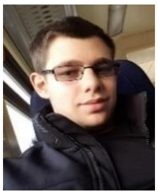
CORRESPONDENCE

Dr Vladan Grković, Assistant Prof.
University of Kragujevac
Fac. of Mechanical and Civil Eng.
Dositejeva 19
36000 Kraljevo, Serbia
grkovic.v@mfkv.kg.ac.rs

Dr Milan Kolarević, Full Prof.
University of Kragujevac
Fac. of Mechanical and Civil Eng.
Dositejeva 19
36000 Kraljevo, Serbia
kolarevic.m@mfkv.kg.ac.rs

Dr Aleksandra Petrović, Asst. Prof.
University of Kragujevac
Fac. of Mechanical and Civil Eng.
Dositejeva 19
36000 Kraljevo, Serbia
petrovic.a@mfkv.kg.ac.rs

Dr Mišo Bjelić, Associate Prof.
University of Kragujevac
Fac. of Mechanical and Civil Eng.
Dositejeva 19
36000 Kraljevo, Serbia
bjelic.m@mfkv.kg.ac.rs



Stefan Pajović, Assistant
University of Kragujevac
Fac. of Mechanical and Civil Eng.
Dositejeva 19
36000 Kraljevo, Serbia
pajovic.s@mfkv.kg.ac.rs