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APPLYING TRIZ AND CMFD TO DESIGN SUSTAINABLE, INTELLIGENT, AND INCLUSIVE BUILDINGS

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Abstract: *Mapping a methodology that can be used to optimize quality of buildings when diverse target functions, like inclusiveness, intelligence and sustainability are taken into consideration is the ambition of this paper. This paper uses a method entitled Concurrent Multi-Function Deployment to review a myriad of criteria (expenditure, occupants' health and comfort) that give the performance of a building in relation with the target functions. Some of the mentioned target functions are negatively correlated and therefore a series of clashes appear, clashes solved with TRIZ. This paper shows that using CMFD and TRIZ one can design and build a solution/a building that is both balanced and stable. This paper tests these methods on a residential building and takes into consideration the three target functions mentioned above. The originality of this paper comes from the multi-criteria and multi-function approach of designing a building to allow the uncompromising integration of ecological aspects in the development of an intelligent and inclusive building.*

Key words: *sustainable building, intelligent, inclusive, TRIZ, cost optimization*

1. INTRODUCTION

In general, if a myriad of norms and principles were considered when designing a practical, cozy and convenient building, one can acknowledge that that building is completed and at its peak. A high-performance building should embody the subsequent peculiarities: abundant comfort in the interior of the building, enduring structure, uplifted energy efficiency, elevated functionality, high productivity, safety, security and well-being of the residents [1], [2]. A sustainable, intelligent and inclusive building is considered to be a high-performance building.

A sustainable building is a building that cumulatively meets several criteria: it uses adequately and at maximum capacity the land on which it is built, it uses water, energy, wood resources, etc. efficiently, it produces resources (energy, water), helps to improve and maintain the health of tenants and increases their productivity, helps strengthen the local economic community, has low carbon dioxide, helps preserve plants, animals and the environment the environment in general protects agricultural, cultural and archaeological resources, is inexpensive to build and live in, and creates a pleasant indoor environment [3].

One of the first complex definitions of smart buildings was given by the Institute of Smart Buildings (IBI), [4], [5]. This definition states that a smart building is a building that ensures productivity by optimizing its four basic elements (systems, structure, services, management) and by interrelating them.

An inclusive building is a building that incorporates all the elements necessary for its efficient and maximum use, without the need for personalization for each inhabitant, including people with disabilities.

2. FUNDAMENTALS

When it comes to multi-dimensional planning for a sustainable, intelligent and inclusive building, a number of questions need to be asked:

- What are the characteristics that highlight the performance of a sustainable building?
- What are the characteristics that highlight the performance of an intelligent building?

- What are the characteristics that highlight the performance of an inclusive building?
- Which of the characteristics are in full agreement and which are antagonistic?
- Can these characteristics be based on measurable and quantifiable parameters? What is the most appropriate / relevant method?
- How is the chosen method tested in the field of constructions?
- Can the results obtained be considered feasible and reliable?

The research path to answer questions on the technical achievements of intelligent, sustainable and inclusive buildings has the following steps: high-performance building features, Sustainable high-performance building features, smart high-performance building features, Inclusive high-performance building features, concordance/antagonism characteristics, feasible and relevant characteristics, substantiation with CMFD, testing and conclusions of buildings.

The Concurrent Multi-Function Deployment (CMFD) method was selected for performance planning based on o multitude of criteria [6]. This method permits a synchronous approach of numerous objective functions while incorporating structured innovation when designing a building.

According to the CMFD algorithm, one must follow a series of steps [6]:

1. Describing the set of objective functions - a set of objectives is defined that is considered sufficient for the solution to have a long-term competitive advantage; each of the objectives is handled by a specialized team
2. Identify and classify, according to importance, the requirements related to the objective and business functions in general - the objective functions must be reported / compared with the investment plans, in order to be able to identify the conflicts that may arise regarding the project
3. Crafting the objective functions - these functions are evaluated with regards to the expenditure plans
4. Analyze, label and determine what value characteristics describe each objective function - each team will assign a set of value characteristics to each function; these value characteristics are measurable, quantifiable and translate into design specifications
5. Produce local solutions for the whole architectural system and its subsystems - for each objective function, the team proposes solutions taking into account the purpose of the project
6. Local solution planning - the value characteristics defined in step 4 are implemented in the subsystem modules
7. Aggregate and innovate in order to develop the entire solution - with the help of an innovative conflict resolution algorithm the complete solution is generated, which represents the combination of local solutions
8. Evaluate the entire universal solution in affinity with the value characteristics - the general solution is analyzed in relation to each value characteristic that corresponds to each objective function
9. The solution as a whole is divided into essential parts and processes - representatives of each team that proposed solutions will detail each of the partial solutions and will define each key feature of that partial solution
10. The essential parts and processes of the solution are synchronously planned - the properties and processes of each partial solution will be analyzed simultaneously in relation to each set of value characteristics that define the objective functions
11. Execution operations planning - each relevant execution parameter for each operation will be planned, taking into account the partial and process processes as a whole.

Criteria such as sustainability, intelligence and inclusiveness will be evaluated and scrutinized, with their bases in the CMFD framework.

3. TESTING AND RESULTS

In order to test the CMFD method we have considered sustainability, intelligence and inclusiveness as objective functions and costs and health of the occupants as requirement functions. The beneficiary, owner of the building about to be designed, has given importance values to each of the functions. The importance valued was chosen by him, based on his preferences with regards to the building.

The objective functions are analyzed in detail, by components, for each requirement in Table 1.

Table 1

The objective functions and their materials and equipment

Objective function	Objects / materials / equipment that meet the objective	Importance percentage (%)
Intelligence	Automatic windows	11%
	Automatic blinds	11%
	Automatic front door	7%
	System that oversees heating	20%
	System that oversees lighting	19%
	Alarm in case of danger	9%
	Automatic lights	7%
	Embedded audio system	4%
	Security system	12%
Sustainability	Protects the environment	9%
	Low energy costs	23%
	Low water usage	20%
	Sturdy/few repairs needed	10%
	Uses recyclable materials	17%
	Furniture build of recyclable materials	5%
	Preserves occupants' health	16%
Inclusivity	Generously spaced bathrooms	13%
	Generously spaced hallways	13%
	Generously spaced rooms	13%
	Unslippery safe floors	12%
	Operate lights effortlessly	7%
	Operate doors effortlessly	9%
	Leveled floors	4%
	Reachable alarm system	12%
	Warning signals	10%
	Brightly lit rooms	7%

Sustainability and intelligence and inclusiveness have positive correlations, as they have characteristic elements that do not necessarily exclude each other, but can work together. On the other hand, there is a negative correlation between sustainability and inclusiveness because these two have characteristic elements that exclude each other. For example, the need for large spaces, which is absolutely necessary for inclusivity, is at odds with sustainability as the latter considers that the existence of large spaces requires additional costs regarding the use of larger quantities of building materials and high costs due to the need to heat these spaces.

In Table 2 one can observe the value characteristics related to sustainability. The highest shares, of 15.02%, is for wall heat transfer coefficient [<0, .40 W/m²k] and the window heat transfer coefficient [<0.70 W/m²k], followed by the carbon emissions level [45% lower] with 14.81%, the degree of recyclability of construction materials [by a minimum of 50% higher than usual constructions] with 13.17%, the surface of windows and doors [max 10% of the surface of walls] with 11.08%, the level of electricity consumption [with min. 50% better than the usual constructions] and the level of thermal energy consumption [with min. 60% better than the usual constructions], both with 10.98%, while the least important is the level of water consumption [with min. 30% better than usual constructions] with 8.93%.

Table 2

Planning the value characteristics associated with sustainability

Links: ☻ powerful link ☺ medium link ℗ possible link	Value characteristics:	Wall heat transfer coefficient [<0,40 W/ m²k]	Heat transfer coefficient of windows [<0,70 W/ m²k]	Carbon emissions [45% lower]	Degree of recyclability of construction materials [at least 50% better than usual constructions]	Surface of windows and doors [max 10% of the surface of walls]	Level of electricity consumption [min. 50% better than usual constructions]	Water consumption level [with min. 30% better than usual constructions]	The level of thermal energy consumption [with min. 60% better than usual constructions]	Degree of importance
No.	Objective	1	2	3	4	5	6	7	8	
1	Protects the environment	☺	☺	☻	☻	☺	☻	☻	☻	9%
2	Low energy costs	☻	☻			☻	☻		☻	23%
3	Low water usage							☻		20%
4	Sturdy/few repairs needed	℗	℗	℗	☻	☻				10%
5	Uses recyclable materials	☺	☺	☻	☻		℗		℗	17%
6	Furniture build of recyclable materials			☻	☻					5%
7	Preserves occupats' health	☻	☻	☻	℗		℗		℗	16%
	Value share	15.02%	15.02%	14.81%	13.17%	11.08%	10.98%	8.93%	10.98%	

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coefficient [<0, .40 W/m²k] and the window heat transfer coefficient [<0.70 W/m²k], followed by the carbon emissions level [45% lower] with 14.81%, the degree of recyclability of construction materials [by a minimum of 50% higher than usual constructions] with 13.17%, the surface of windows and doors [max 10% of the surface of walls] with 11.08%, the level of electricity consumption [with min. 50% better than the usual constructions] and the level of thermal energy consumption [with min. 60% better than the usual constructions], both with 10.98%, while the least important is the level of water consumption [with min. 30% better than usual constructions] with 8.93%.

Table 3

Planning the value characteristics related to intelligence

Links: ☻ powerful link ☺ medium link ℗ possible link	Value characteristics:	Ease of ventilation of the rooms [automatic: closing / opening: 0	Ease of adjusting the brightness [automatic: states 0, 1, 2]	Ease of communication with the outside [data, voice, audio]	Degree of monitoring / surveillance [yard, entrances	Ease of HVAC management [automatic: states 0, 1]	Ease of light management [automatic: 0, 1 states]	Degree of danger prevention [floods, fire]	Degree of importance
No.	Objective	1	2	3	4	5	6	7	
1	Automatic windows	☻	☻		☻	☻	☻	☻	11%
2	Automatic blinds	℗	☻			☻	☻		11%
3	Automatic front door	☻		℗	☻	℗		☻	7%
4	System that oversees heating	℗				☻	℗	☻	20%
5	System that oversees lighting	☻	☻				☻		19%
6	Alarm in case of danger			℗		☺	☺	☻	9%
7	Automatic lights	☺	☻				☻		7%
8	Embedded audio system			☻	℗	☻	℗	℗	4%
9	Security system			☻	☻			☻	12%
Value share		14.17 %	15.90 %	5.89 %	10.08 %	16.49 %	17.78 %	19.69 %	

The planning of value characteristics related to inclusiveness is then calculated. In this case, the highest value if for the degree of accessibility of the rooms [ease of movement: 0.1] with 18.26%, the capacity of visual warning [ease of observation: 0, 1] with 15.64%, followed by the degree of accessibility on the hallways [ease of movement: 0, 1] and the degree of accessibility of the bathroom [ease of use: 0, 1, 2], both with 14.61%. These are followed at a short distance by the audible warning capacity [audio ease: 0, 1] with 14.33%. On the last positions are the degree of coverage with natural lighting [degree of coverage: 0, 1, 2] with 8.33%, the ease of access to the building [automatic: degree of difficulty: 0, 1, 2] with 6.55% and the ease access to the upper level [speed min. 0.6m / s] with 4.78%. In last place is the degree of accessibility to any piece of furniture [ease of use: 0, 1, 2] with 2.90%.

Table 4

The components of the solution, at the level of generic modules, related to sustainability

Links: ☻ powerful link ☺ medium link ℗ possible link	Value	Doors	Windows	Walls	Furniture	Electricity	Thermal	Water	HVAC	Light	Degree of importance
No.	Objective	1	2	3	4	5	6	7	8	9	
1	Wall heat transfer coefficient [<0,40 W/ m²k]			☻			☻		☻		15.02 %
2	Heat transfer coefficient of windows [<0,70 W/ m²k]	☻	☻				☻		☻		15.02 %
3	Carbon emissions [45% lower]	☻		☻	☻	☺	☺				14.81 %
	Degree of recyclability of construction materials [at least 50% better than usual constructions]	☻	☻	☻	☻			℗			13.17 %
5	Surface of windows and doors [max 10% of the surface of walls]	☻	☻	☻		☺	☻			☻	11.08 %
6	Level of electricity consumption [min. 50% better than usual constructions]		☻			☻				☻	10.98 %
7	Water consumption level [with min. 30% better than usual constructions]							☻			8.93 %
8	The level of thermal energy consumption [with min. 60% better than usual constructions]	☻	☻	☻			☻		☻		10.98 %
Value share		17.61%	16.57%	17.61%	7.57%	5.31%	15.44%	2.81%	11.10%	5.97%	

Below are the local solutions, which emphasize an objective function. For the elaboration of the local solutions the indications from the associated planning matrices were taken into account (Tab. 4, Tab. 5, Tab. 6).

Table 3 highlights the planning of intelligence-related value characteristics. With the highest share is the degree of danger prevention [floods, fire] with 19.69%, followed by the ease of light management [automatic: states 0, 1] with 17.78%, the ease of HVAC management [automatic: states 0, 1] with 16.49%, the ease of adjusting the brightness [automatic: states 0, 1, 2] with 15.90%, the ease of ventilating the rooms [automatic: closing / opening: 0, 1] with 14.17% and the degree of monitoring / surveillance [yard, entrances, interior] by 10.08%. On the last place is the ease of communication with the outside [data, voice, audio] by 5.89%.

Table 5

The components of the solution, at the level of generic modules, related to intelligence

Links: ☻ powerful link; ☺ medium link; ℗ possible link

No.	Objective	Windows	Building surveillance	HVAC monitoring	Light monitoring	Communication system	Danger monitoring /	Degree of importance
		1	2	3	4	5	6	
1	Ease of ventilation of rooms [automatic: closing / opening: 0, 1]	☻		☻				14.17%
2	Ease of dimming [automatic: states 0, 1, 2]	☻			☻			15.90%
3	Ease of communication with the outside [data, voice, audio]					☻	☻	5.89%
4	Degree of monitoring / surveillance [yard, entrances, interior]		☻	☻	☻	☺	☻	10.08%
5	Ease of HVAC management [automatic: states 0, 1]	☻		☻				16.49%
6	Ease of light management [automatic: 0.1 states]	☻	☻		☻			17.78%
7	Degree of danger prevention [floods, fire]		☻			☻	☻	19.69%
	Value share	24.65 %	18.22 %	15.61 %	16.77 %	11.09 %	13.66 %	

Taking into account the value of the percentages obtained for each and every component related to sustainability, intelligence and inclusivity, we have designed a hybrid building, hybridizing the two objective functions that have positive correlations: sustainable and intelligent.

Table 6

The components of the solution, at the level of generic modules, related to inclusiveness

Links: ☻ powerful link; ☺ medium link; ℗ possible link

No.	Objective	Access ways	Doors	Vertical	Rooms	Bathroom	Floor	Furniture	Danger monitoring /	Communicat	Degree of importance
		1	2	3	4	5	6	7	8	9	
1	Ease of access to the upper level [speed min. 0.6m /s]	☺		☻			☺				4.78 %
2	Ease of access to the upper level [speed min. 0.6m / s]	☻	☻				☻				14.61%
3	Accessibility of the bathroom [ease of use: 0, 1, 2]		☻			☻	☻	☻	☺		14.61%
4	Accessibility of the rooms [ease of movement: 0, 1]	☻	☻		☻		☻	☻			18.26%
5	Degree of accessibility to any piece of furniture [ease of use: 0, 1, 2]							☻			2.90 %
6	Visual warning capability [ease of observation: 0, 1]	☻	☻	☻	☻	☻	☻	☻	☻	☺	15.64%
7	Auditory warning ability [audio ease: 0, 1]	☻	☻	☻					☻	☻	14.33%
8	Ease of access to the building [automatic: degree of difficulty: 0, 1, 2]	☻	☻				☻		☺	☺	6.55 %
9	Natural lighting [coverage: 0, 1, 2]	☺	☺	☺	☻	☺					8.33 %
	Value share	16.22	19.08	8.25	9.29	7.26	15.67	11.30	8.14 %	4.78	

The smart sustainable building in Figure 1 is made of load-bearing masonry 30 cm with 25 cm pits of reinforced concrete, 5 cm leveling system up to the masonry, basalt mineral wool thermal system 20 cm. The floors are made of 25 cm tiles, there are no beams visible anywhere in the house. The carpentry is made of aluminum with 2 sheets of double glazing, and between the two sheets there is incorporated an automatic system of blinds. The terrace and the roof have the following stratification: interior finish, plaster, 13-15 cm reinforced concrete slab, diffusion layer, vapor barrier, extruded polystyrene thermal insulation, where it is walkable, and expanded, where it is non-walkable, thermal insulation protection layer, reinforced screed 5 cm, 1-2% sloping concrete, waterproofing and waterproofing protection layer (wood or sandstone floor for the circulated one and granular gravel for the uncirculated one).

Bathrooms and dressing rooms have a built-in smart room recognition system: the glass becomes opaque when the room is used. The heating is done by an electrical system supported only in a small proportion, of 10%, by a system of batteries supplied by the photovoltaic system. Remote control is one of the features of this building and it encompasses remote controlling the heat, the water consumption, the energy consumption, the light, the security system, the doors etc. If some of the rooms are not occupied, after a certain amount of time has passed, the ventilation, the heat and the microsystem in that rooms close.

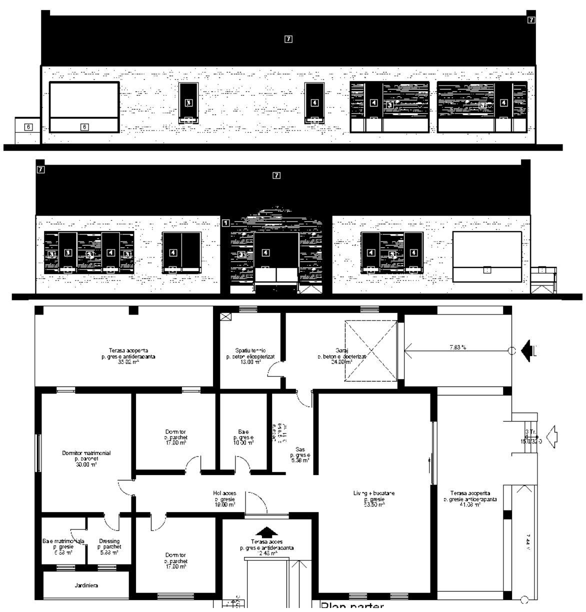

Fig. 1. North façade, south façade, ground floor sustainable intelligent building (from top to bottom)

After designing the sustainable intelligent building, we have tried to combine this building with the inclusive one, and the result was an intelligent, sustainable, inclusive building.

Following the calculations in Table 7, the importance of each component of a sustainable, inclusive and intelligent building can be concluded: the importance of windows is the highest, at 15.29%, superseded by the doors at are situated at 12.37% and the HVAC monitoring system which is at 9.96%. In last place one can observe: the communication system (audio, video, data) with 4.62%, the access ways with 3.76%, the floor with 3.63%, the electricity supply system with 2.40%, the rooms with 2.15%, the vertical circulation that is at the value of 1.91%, the bathroom at the value of 1.68% and the water supply system, situated last in this ranking, at 1.27%.

Table 7

Total final weight of components

No.	Final solution component	**Sustainability**		**Intelligence**		**Inclusivity**		Total final weight (%)
		PV	PF1 (%)	PV2	PF2 (%)	PV	PF3 (%)	
1	Doors	0.451	17.61%	0.317		0.231	19.08%	12.37%
2	Windows		16.57%		24.65%			15.29%
3	Walls		17.61%					7.95%
4	Furniture		7.57%				11.30%	6.03%
5	Electricity supply system		5.31%					2.40%
6	Thermal energy supply system		15.44%					6.97%
7	Water supply system		2.81%					1.27%
8	HVAC monitoring system		11.10%		15.61%			9.96%
9	Light monitoring system		5.97%		16.77%			8.01%
10	Building surveillance system				18.22%			5.78%
11	Communication system (audio, video, data)				11.09%		4.78%	4.62%
12	Danger monitoring / warning system				13.66%		8.14%	6.22%
13	Vertical circulation						8.25%	1.91%
14	Rooms						9.29%	2.15%
15	Bathroom						7.26%	1.68%
16	Floors						15.67%	3.63%
17	Access ways						16.22%	3.76%

When combining the intelligent sustainable building with the inclusive one, discords emerged in the design phase (Fig.2). These conflicts can be settled using the Theory of Inventive Problem Solving (TRIZ) and its principles. TRIZ is a tools that helps specialists in all areas of expertise translate some very specific problems one needs to solve into generic problems that can be translated into 40 universal principles [7], [8].

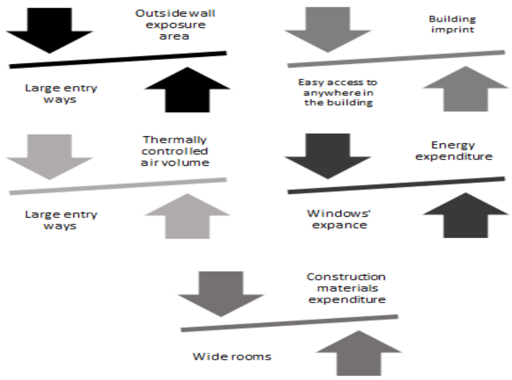

Fig. 2. Conflicts when designing an intelligent, sustainable and inclusive building

For example, the owner wanted to spend as little as possible on construction materials, but he also wanted his house to have wide, large rooms. Using TRIZ, we have translated his demands into parameters: "amount of material" and "moves inside a stationary object". Once doing this, TRIZ offers principles for fixing these disputes: the principle of composite materials, the principle of local quality and the principle of changing parameters. With the help of the composite materials principle, this dispute was settled. Recycled materials should be used in the development of the construction.

To resolve the conflict: "smallest possible building imprint" and "easy access anywhere in the building" TRIZ selected the adherent parameters: "convenience in use" and "surface of stationary objects". In fixing these disputes, TRIZ offers several principles: the principle of asymmetry, and the principle of partial or excessive actions. Both principles have been combined to resolve this conflict. According to the principle of asymmetry, the upper level of the house is smaller in surface than the ground level. According to the "excessive actions" principle, the installation of a hydraulic platform was chosen, for access to the upper floor.

The conflict: a large windows' expanse and as low as possible energy expenditure has the subsequent TRIZ principles: the principle of flexible/thin materials, the principle of transfer in another dimension and the nest-in-nest principle. To solve these problems, an automatically operated roller shutter system was implemented. This system helps to transfer indoor and outdoor heat. The roller shutters also lower automatically if there is too much natural light in the room.

Taking all these conflicts and their solutions into consideration (Fig. 2), while also taking into account the total final weight of components (Tab. 7), the sustainable, inclusive and intelligent house was designed (Fig.3).

The sustainable, intelligent and inclusive building in Figure 3 has two levels, its walls are coated in thermal insulation built out of recyclable materials. 30 cm load-bearing masonry with 25 cm pits of reinforced concrete with 5 cm masonry heating system, 25 cm belts, 5 cm basalt mineral wool (or polystyrene), masonry heating and 15 cm heating system can be found within the walls. The carpentry is made of 90 mm laminated wood, with 3 sheets of double glazing, it is mounted on a metal structure outside the masonry wall, in the heating system. and will save 15% on total heat consumption over the entire life of the building. The glass reflects sunlight. Treated recycled plywood and recycled brick are the materials from which the exterior finished were made of.

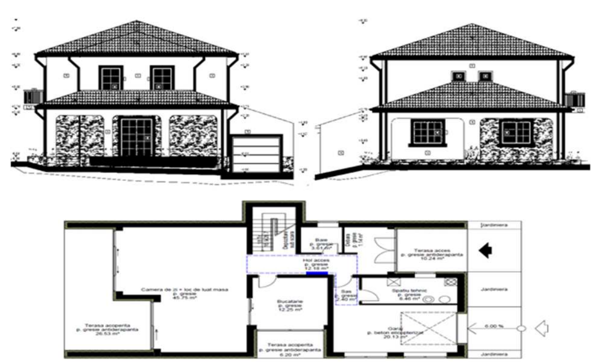

Fig. 3. North façade, south façade, ground floor sustainable intelligent inclusive building (from top to bottom)

The plumbing is distributed in the building through the lobby in the central position, thus saving both in terms of materials and in terms of the fact that the ventilation plant has a much shorter journey. A geothermal pump heats the house through floor heating. This geothermal pump is also able to chill the house's walls during hot summers and warm the walls during frosty winters.

Remote control in terms of energy usage, water consumption, heat and light is embedded in the building. Bathrooms and dressing rooms did not incorporate intelligent systems, as in the hybrid building as the windows have a parapet of 1.90 m, they are operated from the remote control / telephone / switch, both for the opening system and for the roller shutters, they are not accessible otherwise for people with disabilities. This system was chosen because of the privacy coefficient that was reported in terms of costs.

4. CONCLUSIONS

As global trends in construction have begun to move beyond one's desire to develop simplistic buildings into the development of buildings of the future: sustainable, smart or inclusive buildings, this paper wishes to devise a draft procedure/technique on how optimization in terms of quality can be handled when these types of buildings converge into a single entity.

When a variety of target functions are taken into consideration (intelligence, inclusiveness, sustainability) this paper establishes that it is feasible to design an equitable and stable solution with respect to the building industry.

The limitation of this study is that is was only applied on a relatively small residential building and taking into consideration only three target functions.

However, we believe this technique is a stepping stone necessary for all professionals in the construction industry, when tackling a project such as the one presented above.

Undeniably, this methodology needs further research in the event of it being applied on more complex civil engineering projects, research that we are willing and able to make in the future.

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APLICAREA TRIZ ȘI CMFD LA PROIECTAREA CLĂDIRILOR SUSTENABILE, INTELIGENTE ȘI INCLUSIVE

Abstract: Ambiția acestei lucrări este cartarea unei metodologii care poate fi utilizată pentru a optimiza calitatea clădirilor atunci când sunt luate în considerare diverse funcții țintă, cum ar fi incluzivitatea, inteligența și sustenabilitatea. Această lucrare utilizează o metodă intitulată Implementare multifuncțională simultană pentru a revizui o multitudine de criterii (cheltuieli, sănătatea și confortul ocupanților) care oferă performanța unei clădiri în raport cu funcțiile țintă. Unele dintre funcțiile țintă menționate sunt corelate negativ și, prin urmare, apar o serie de conflicte, conflicte rezolvate cu TRIZ. Această lucrare arată că folosind CMFD și TRIZ se poate proiecta și construi o soluție / o clădire echilibrată și stabilă. Această lucrare testează aceste metode pe o clădire rezidențială și ia în considerare cele trei funcții țintă menționate mai sus. Originalitatea acestei lucrări provine din abordarea multi-criterială și multifuncțională a proiectării unei clădiri pentru a permite integrarea fără compromisuri a aspectelor ecologice în dezvoltarea unei clădiri inteligente și incluzive.

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