Application of MCDM and BIM for Evaluation of Asset Redevelopment Solutions

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Abstract: The current paper analyses the application of Multiple Criteria Decision Making (MCDM) and Building Information Modelling (BIM) techniques for integrated information management when assessing redevelopment solutions of former industrial buildings with emphasis on sustainable development. The theoretical approach of complex decision-making model for asset redevelopment is proposed and practical case study of old equipment factory redevelopment is presented. Sixteen criteria combined in three groups as economic, environmental and technological indicators are analysed both with ranking of possible redevelopment alternatives of the building using Weighted Aggregated Sum Product Assessment method with grey attributes scores (WASPAS-G). The selection of the most rational redevelopment solution for analysed projects is also supported by BIM techniques and allows implementation of whole project life-cycle management strategy in real life.

Keywords: information management, sustainable asset redevelopment, MCDM, WASPAS-G, BIM, building life cycle.

1. Introduction

Reliable techniques are necessary to manage construction project information flows as well as to reduce uncertainties and risks when solving technological and economic challenges in construction with effective decision support [2, 12, 24]. Analysing possibilities of application of automated design and information management [17], the need for delivering mutual information in a timely manner between all the responsible and competent participants, data archiving and working in a common area with a unified computer-aided design system tools is emphasized [1, 26, 27].

Building Information Modelling (BIM) is now globally considered to be a universal digital technology which is argued to have the potential to revolutionise information management in construction industry [1, 20]. A number of studies about researches in the area as well as BIM implementation can be found, but it is dominated by application to new buildings, while conversion of existing assets or reconstruction not yet widely supported [4, 27]. However, with regard to progressive ideas of sustainable development and sustainable construction, more attention should be given to redevelopment of abandoned assets instead of expanding new urban areas and erecting new buildings. Much attention is paid to redevelopment of urban areas, including problematic issues to be addressed, analysis of potential solutions and their social and economic efficiency justification [16].

It is claimed, that due to successful redevelopment the assets become more attractive to live or to invest [6, 14], produce economic and environmental savings [10, 18]. However, proper methods and tools are important to manage the information and to take the most effective solution [8, 13].

The solutions can be supported by different digital construction techniques [2, 17], but BIM can be considered to be the best technique ensuring the quality of project [1, 21, 26]. It is applicable in any project lifecycle phase and involves a lot of benefits both for new construction and existing assets [20, 27] to ensure project information and quality control.

Every solution needs to be evaluated in regard to a lot of technical, economic, social and environmental indicators, such as physical condition of load-bearing structures, historical and architectural value of the building or area, infrastructure, potential contamination of the territory, carbon emissions [13, 34]. Strategic solutions regarding redevelopment of existing assets usually should be evaluated with respect to sustainability, building heritage and modern demands [3, 5, 15, 23]. Therefore Multiple Criteria Decision Making (MCDM) can be useful for handling numerous information and for decision support [11, 28, 29].

Uncertainty of information and risk level are the largest in the beginning of construction project, while their influence decline to an acceptable level in the elaboration of the information in the course of the project, i.e. adjusting the data over the entire building lifecycle. Therefore, the most important is to manage and control the information at the beginning of a project and to select the most effective solution.

Accordingly, the aim of the current research is to suggest application of MCDM and BIM techniques for integrated information management, when selecting and implementing the most effective sustainable asset redevelopment solution. Integrated decision-making model, emphasizing interconnections between the techniques, is presented in Chapter 2. Due to high level of uncertainty, using Weighted Aggregated Sum Product Assessment method with grey numbers is suggested. A case study of abandoned industrial building redevelopment, involving 3D modelling and multiple criteria evaluation, is presented in Chapter 3.

The outcomes of the study revealed that the suggested information management and decision-making model is a reliable technique for project selection and management in uncertain environment. The objectives of the study were effectively attained by determining the priority order of the analysed asset redevelopment solutions and making it possible to implement the selected project using Digital Construction techniques.

2. Methodology for Evaluation of Asset Redevelopment Solutions

2.1 Asset management decision-making using MCDM and BIM techniques

This specific subtopic of the implementation of new Digital Construction techniques (like geospatial GIS, 3D Laser Scan and BIM) was found as new research field partially analysed in some scientific works [1, 15]. The best practice, knowledge, experience and "know-how" [26, 27] leads world to new approach of connecting traditional survey methods with design process and innovative technologies in construction industry [5, 22, 17].

Different types of solutions can be used to combine most advanced ICT (Information and Communication Technologies) and BIM techniques in building industry for every stage of asset implementation (steps are listed below):

- For new design of asset. First step is to prepare initial 3D model for new building, civil engineering object/system or other new asset, second step is to make BIM model with interoperability check between all project design parts [1, 26, 27], participants, third step is to check the BIM model requirements related to environment and geospatial situation to analyse quality for design, forth step is to prepare for tendering of construction works and make evaluated investment project according to asset design.
- For asset construction quality control on site. First step is to prepare quality analysis plan both connected with design BIM model and construction BIM model [17, 22], second step is to make quality assessment of completed underground structure, underground engineering utilities, and aboveground structure related with geospatial information (all GIS dimensions) and real implementation, third step is to make day-by-day „As-build" model with 3D laser scan technologies and analyse interferences according to BIM model, forth step is to make the quality assessment of completed construction works before handover of asset.
- For existing asset and redevelopment. First step is to choose GIS positions and perform 3D laser scanning of existing building, civil engineering object/system or other asset and this is especially helpful without available as-built drawings or records, second step is to combine collected point cloud data and from primitives make identified 3D model [21], third step is to connect 3D model with all accessible information [4] and also interconnect GIS and BIM models [15], forth step is to make new BIM design and implementation of redeveloped asset.

All solutions can be used simultaneously with assessment of alternative design and with MCDM methods including precise criteria information from BIM model (such as quantity take-offs, implementation time and project cost). Also at completion of any stage of asset project implementation, received information (collected during design, construction, maintenance or refurbishment) is interconnected and transferred to an integrated GIS, BIM and AIM (asset information management) system as implementation of most advanced ICT to support redevelopment activities and asset management.

Different building redevelopment concepts can be analysed: property refurbishment (renovation), conversion to other uses, or demolition an old structure and building a new one. The selection of the best concept considering a set of quantitative and qualitative criteria, emphasising sustainable development according to algorithm of a novel Weighted Aggregated Sum Product Assessment method with grey attributes scores (as it is presented in Subchapter 2.3) and BIM techniques supports an effective selection process and further implementation of a project (see Figure 1).

2.2 Criteria system for assessment of buildings redevelopment

All the time when decision needs to be made the question appears, is it better to make refurbishment, demolition and new construction or conversion. Analysing from the aspects of sustainable development, a decision is influenced by a group of economic, environmental and technological indicators, such as physical condition of load-bearing structures, historical and architectural value of the building, location, infrastructure, potentially contaminated areas, and others.

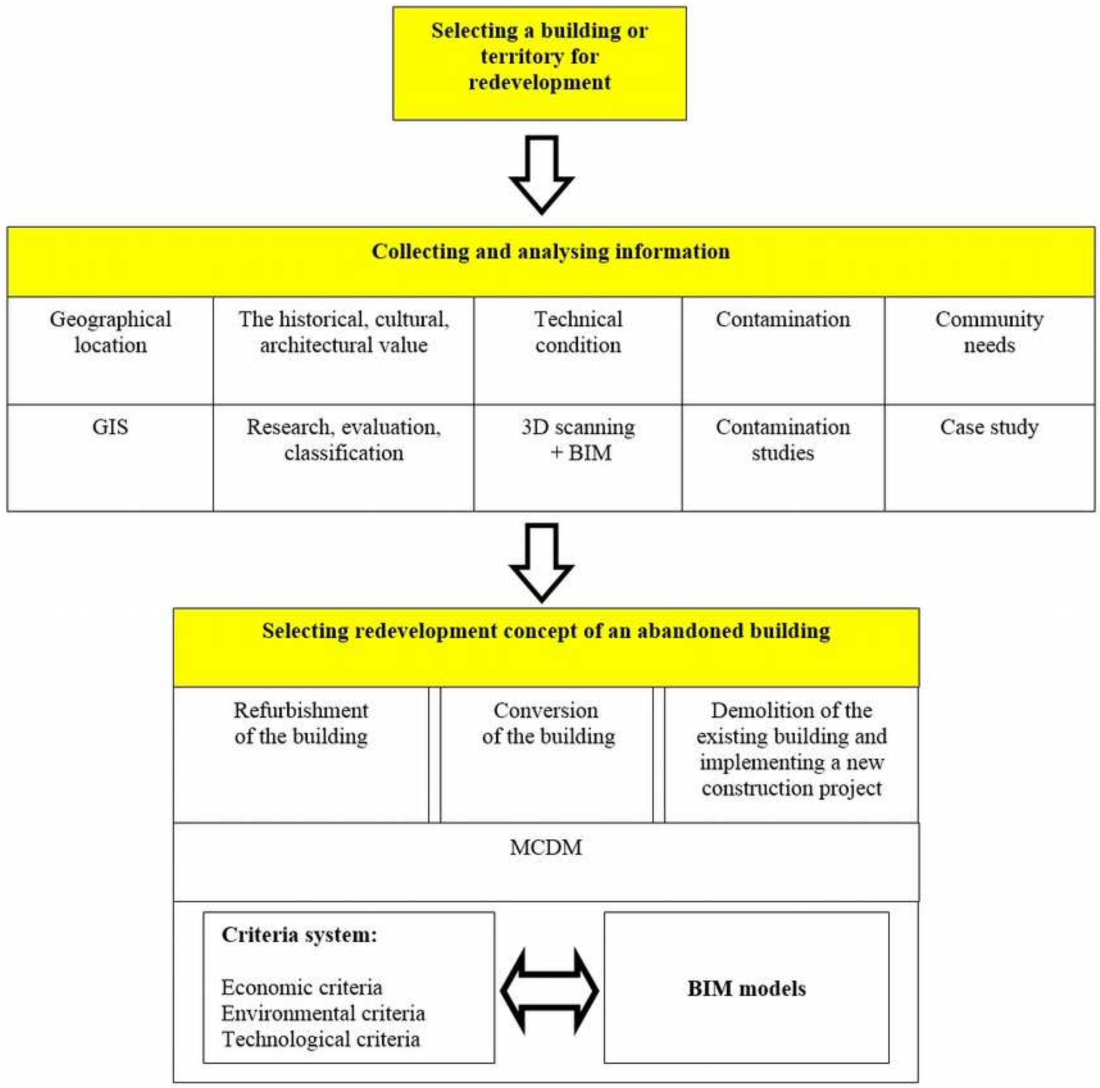

Figure 1. Complex evaluation model from perspective of project life cycle management

Conversion of buildings is more appropriate because of the longer life of materials and reduced consumption of energy and other resources, reduced CO_2 emissions. However, such works are of greater technological complexity. Also, one can face with limited old building application to contemporary needs. The listed factors have an impact on the return on investment.

Accordingly, it is proposed to apply complex criteria system, consisting of three sub-systems: technological criteria sub-system, economic criteria sub-system, and environmental criteria sub-system. Composition of the system is presented in Figure 2. The criteria are further used for a case study as presented in Chapter 3.

2.3 WASPAS-G for multiple-criteria decision-making

Weighted Aggregated Sum Product Assessment method with grey numbers (WASPAS-G) is a novel method, presented in 2015 and applied for contractor selection [31]. It is an extension of an original crisp WASPAS method as presented by Zavadskas et al. in 2012 [32]. Other available developments of the method in a vague environment involve extension with interval-valued intuitionistic fuzzy numbers, named WASPAS-IVIF [28], also a hybrid approach combining the method with fuzzy numbers (WASPAS-F) and Analytical Hierarchy Process (AHP), proposed by Turskis et al. in 2015 [25] and applied for site selection. To apply any of decision-making methods in uncertain environment with the help of grey numbers, Deng concepts of grey theory [9] should be realized. Based on Chen and Tzeng classification of information into three groups according to uncertainty level [7], let $\otimes x = [\alpha, \beta]$ to be a grey number with the lower and the upper limit. Initial decision-making matrix is then composed of grey numbers $\otimes x_{ij} = [x_{ij\alpha}, x_{ij\beta}]$, where x_{ij} are values of alternatives assessment criteria, $i = 1, \ldots, m; j = 1, \ldots, n; m$ is number of alternatives, n is number of criteria according to grey system theory [19].

Initial values of criteria are normalized by applying a linear method. Criteria with preferred maximal values are suggested to be normalized as follows:

$$\otimes \bar{x}_{ij} = \frac{\otimes x_{ij}}{\max_i \otimes x_{ij}}, \quad i.e.\ \bar{x}_{ij\alpha} = \frac{x_{ij\alpha}}{\max_i x_{ij\beta}}\ and\ \bar{x}_{ij\beta} = \frac{x_{ij\beta}}{\max_i x_{ij\beta}}. \tag{1}$$

Criteria with preferred minimal values are normalized as:

$$\otimes \bar{x}_{ij} = \frac{\min_i \otimes x_{ij}}{\otimes x_{ij}}, \quad i.e.\ \bar{x}_{ij\alpha} = \frac{\min_i x_{ij\alpha}}{x_{ij\beta}}\ and\ \bar{x}_{ij\beta} = \frac{\min_i x_{ij\alpha}}{x_{ij\alpha}}. \tag{2}$$

The normalized weighted values of criteria $\otimes \hat{x}_{ij}$ are calculated multiplying the

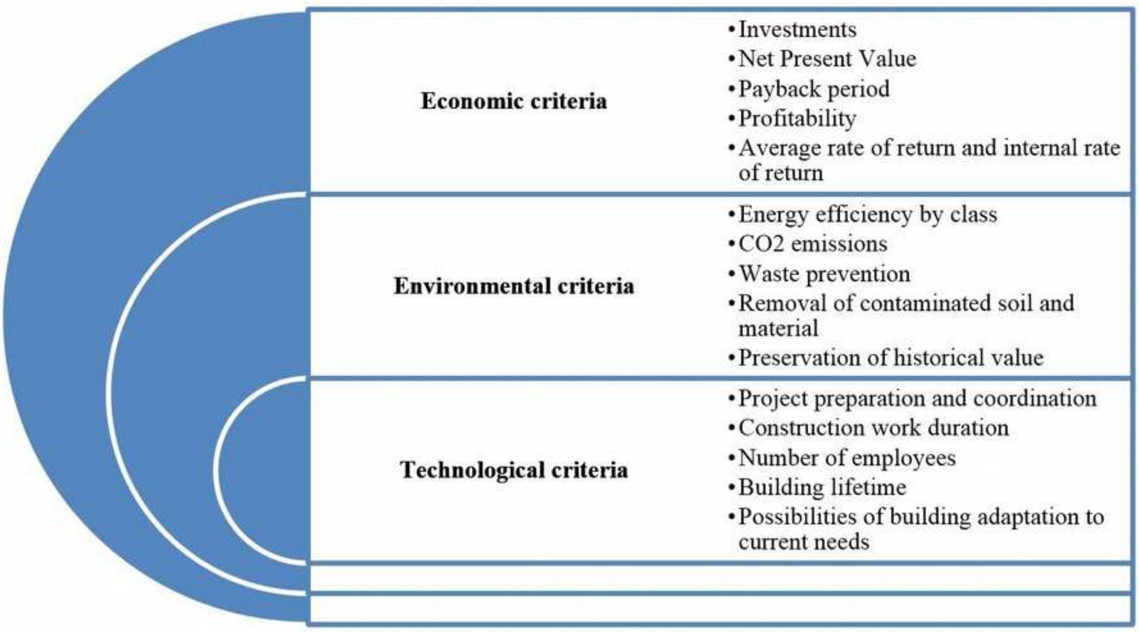

Figure 2. Criteria system for evaluation of assets redevelopment solutions

normalized values $\otimes \bar{x}_{ij}$ by the weights (relative significances) of criteria $\otimes w_j$.

The first member of aggregated optimality function of alternatives with grey values $\otimes S_i$ is suggested to be calculated as follows:

$$\otimes S_i = \sum_{j=1}^{n} \otimes \hat{x}_{ij}, \text{ or}$$
$$\otimes S_i = 0.5 \sum_{j=1}^{n} \left(\hat{x}_{ij\alpha} + \hat{x}_{ij\beta} \right). \quad (3)$$

The second member of aggregated optimality function of alternatives with grey values $\otimes P_i$ is calculated as follows:

$$\otimes P_i = \prod_{j=1}^{n} \otimes \bar{x}^{\otimes w_j}, \text{ or}$$
$$\otimes P_i = \prod_{j=1}^{n} 0.5 \left(\otimes \bar{x}_{j\alpha}^{\otimes w_j} + \otimes \bar{x}_{j\beta}^{\otimes w_j} \right). \quad (4)$$

Accordingly, the weighted aggregation of grey optimality functions [31]:

$$\otimes Q_i = \lambda \otimes S_i + (1-\lambda) \otimes P_i =$$
$$= \lambda \sum_{j=1}^{n} \otimes \hat{x}_{ij} + (1-\lambda) \prod_{j=1}^{n} \otimes \bar{x}^{\otimes w_j}. \quad (5)$$

Aggregation coefficient $\lambda = 0, \ldots, 1$ and it is suggested to be determined as follows [31]:

$$\lambda = 0.5 \frac{\sum_{i=1}^{m} P_i}{\sum_{i=1}^{m} S_i}. \quad (6)$$

P_i and S_i are crisp values of optimality functions. They are transformed from grey values $\otimes S_i$ and $\otimes P_i$ by using the centre-of-area method.

Ranking order of alternatives is determined according to the Q_i, after transforming the grey values of $\otimes Q_i$ to crisp values by the centre-of-area method.

3. Case Study: Ranking of Alternatives

3.1 Description of case study object

The object of case study is old equipment repair factory, located in Vilnius (Lithuania). Both the initial and actual images and data transfer management through life cycle of the building (with information model for initial and refurbished building) as well as prepared information model of the existing building are presented in Figure 3.

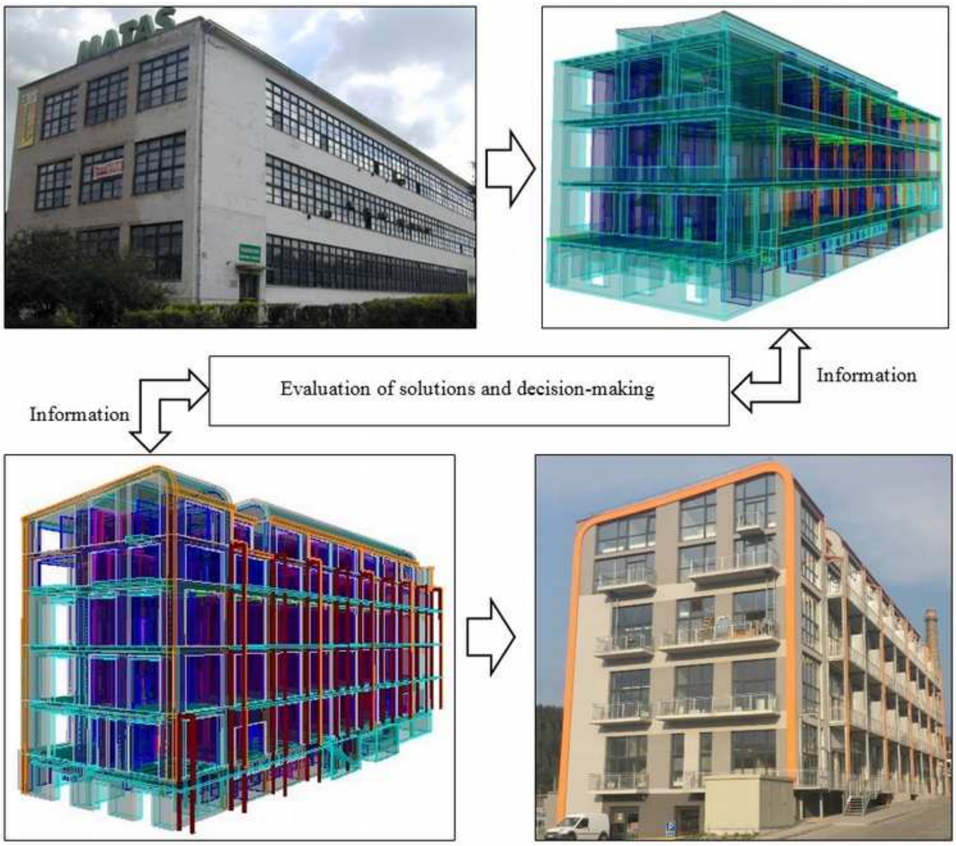

Figure 3. Information management and decision-making model

In the paper three alternatives of asset redevelopment are evaluated, including building refurbishment and adaptation to current needs while maintaining or slightly changing the original object and its historically established purpose (a_1), refurbishment of the building into loft-type housing, preserving its architectural-urban expression (a_2), demolition of the existing building and implementing a new construction project (a_3).

Selection of the most preferable conversion alternative of industrial building is analysed regarding to a set of criteria as described in Subchapter 2.2. Considered criteria include investments, millions EUR (x_1); Net Present Value, millions EUR (x_2); payback period, years (x_3); profitability index (x_4); average rate of return, percent (x_5); internal rate of return, percent (x_6); project preparation and coordination, months (x_7); construction work duration, months (x_8); number of employees, persons (x_9); building lifetime, years (x_{10}); possibilities of building adaptation to current needs, percent (x_{11}); energy efficiency by class (x_{12}); preservation of historical value, points (x_{13}); CO_2 emissions, percent (x_{14}); removal of contaminated soil and material, percent (x_{15}); waste prevention, points (x_{16}). Criteria x_1, x_3, $x_7 - x_9$, $x_{11} - x_{12}$ and x_{14} are minimized, while the remaining are maximized in a process of optimization. Weights of attributes obtained using expert survey. Interviewed 10 experts, including heads of construction companies, engineers, environmental protection, and heritage specialists.

Initial decision-making matrix, describing conversion alternatives in terms of economic criteria, as well as ranking results applying WASPAS-G method (Eq. 1-6) are presented in Table 1. Initial decision-making matrix, describing conversion alternatives in terms of technological criteria, as well as ranking results applying WASPAS-G method are presented in Table 2. Also initial decision-making matrix, describing conversion alternatives in terms of environmental criteria, and multiple-criteria ranking results are presented in Table 3.

3.2 Case study results

By preserving the building facades, some of the structural or technical details, it is possible to create unique objects. It is proved that in terms of sustainable development the conversion of buildings is more suitable, because the longer lifespan of the materials reduces the energy and resource consumption, CO_2 emissions. A new generation of building information management techniques significantly simplifies the design, construction and operation of the buildings, making these processes more efficient.

Table 1. Initial decision-making matrix and rankings in terms of economic criteria

Alternatives a_i	***Initial criteria values*** $\otimes x_{ij}$												***Ranking results***			
	$\otimes x_1$		$\otimes x_2$		$\otimes x_3$		$\otimes x_4$		$\otimes x_5$		$\otimes x_6$		***Values of functions***			***Rank***
	a	*β*	*a*	*β*	*a*	*β*	*a*	*β*	*a*	*β*	*a*	*β*	P_i	S_i	Q_i	
a_1	1.00	1.20	0.47	0.27	3.25	3.96	1.53	1.25	72.0	60.0	26.0	17.0	0.528	0.615	0.567	3
a_2	2.50	2.80	0.96	0.79	1.75	1.81	1.60	1.50	77.5	72.5	36.0	31.0	0.647	0.690	0.666	2
a_3	3.40	4.10	0.89	1.38	0.93	0.83	1.30	1.36	58.7	61.1	34.0	41.0	0.683	0.746	0.712	1
Weights $\otimes w_j$	0.191		0.151		0.182		0.154		0.168		0.154		$\sum P_i = 1.858$	$\sum S_i = 2.052$	$\lambda = 0.453$	

Remark: Ranking results calculated according to equations presented in Chapter 3 and BIM model information

Table 2. Initial decision-making matrix and rankings in terms of technological criteria

Alternatives a_i	***Initial criteria values*** $\otimes x_{ij}$										***Ranking results***			
	$\otimes x_7$		$\otimes x_8$		$\otimes x_9$		$\otimes x_{10}$		$\otimes x_{11}$		***Values of functions***			***Rank***
	a	*β*	*a*	*β*	*a*	*β*	*a*	*β*	*a*	*β*	P_i	S_i	Q_i	
a_1	4.00	5.00	6.00	7.00	56	56	32.00	32.00	20.00	30.00	0.571	0.672	0.616	1
a_2	9.00	11.00	14.00	16.00	178	178	80.00	80.00	70.00	80.00	0.503	0.540	0.519	3
a_3	6.00	7.00	16.00	18.00	190	190	100.0	100.0	100.0	100.0	0.581	0.657	0.615	2
Weights $\otimes w_j$	0.184		0.230		0.176		0.200		0.210		$\sum P_i = 1.656$	$\sum S_i = 1.869$	$\lambda = 0.443$	

Remark: Ranking results calculated according to equations presented in Chapter 3 and BIM model information

Table 3. Initial decision-making matrix and rankings in terms of environmental criteria

Alternatives ***a_i***	***Initial criteria values*** $\otimes x_{ij}$										***Ranking results***			
	$\otimes x_{12}$		$\otimes x_{13}$		$\otimes x_{14}$		$\otimes x_{15}$		$\otimes x_{16}$		***Values of functions***			***Rank***
	α	β	α	β	α	β	α	β	α	β	P_i	S_i	Q_i	
a_1	1.00	1.50	9	10	20.00	30.00	5.00	10.00	8	9	0.441	0.610	0.510	2
a_2	0.38	0.50	7	8	55.00	60.00	50.00	60.00	7	8	0.650	0.686	0.664	1
a_3	0.38	0.50	1	2	100.0	100.0	80.00	90.00	2	2	0.363	0.495	0.417	3
Weights $\otimes w_j$	0.238		0.188		0.206		0.188		0.180		$\sum P_i = 1.454$	$\sum S_i = 1.792$	$\lambda = 0.406$	

Remark: Ranking results calculated according to equations presented in Chapter 3 and BIM model information

In this research the information management of completed digitalization procedures and prepared information model were used for building redevelopment alternatives' evaluation. This was validated by a number of benefits that ensured decision-making and information management quality by using BIM and MCDM techniques for analysed redevelopment project:

- Interference detection, clash control, arrangement of all design parts in virtual environment before construction;
- Virtually tested design for tendering and evaluation process (with precise quantity take-offs);
- Precise quantity take offs of demolishing to evaluate impact to environment;
- Collaboration between project participants and ensuring information quality control;
- Better communication with client using visualisation and common language;
- Spatially organized information of facility data in one BIM model;
- Actual digitalised information of present and new elements is especially helpful on renovation projects (without as-build documentation);
- Effective project and asset management;
- Effective building construction process, reduction of time waste and better quality control;
- Reducing project risk and costs;
- Reliable project information management and decision-making.

It is confirmed that combining available data of the project, geospatial situation, information about project, analysis of actual situation and laser scanning is mostly applied to existing buildings and other asset, but applications for new construction or redevelopment project works are necessary to complete the integrated BIM cycle, to provide an added value of the integrated BIM workflow and to ensure the success of information management with control of the project implementation quality.

The detail results after evaluation of asset redevelopment solutions using BIM and MCDM techniques:

- From the economic aspects, it was found that the most beneficial is alternative a_3 - demolition of the existing building and implementing a new construction project (Table 1). The a_2 alternative - refurbishment of the building into loft-type housing – is not far behind, its utility is less by 7 percent when comparing to a new construction alternative;
- Technological complexity of new construction or reconstruction works of an old building when maintaining its initial purpose was assessed as almost equal. Values of weighted aggregated optimality function Q_1=0.616 and Q_2=0.615, respectively (Table 2). Alternative of refurbishment of the building into loft-type housing is evaluated worse by 15 percent in terms of technological criteria of construction works;
- When emphasising environmental aspects in a time of construction works and further operation of refurbished assets, the best alternative is conversion of the industrial building into loft-type housing. It gains significant advantage when compared to other analysed alternatives. Conversion into loft-type housing is up to 37 percent better than a new construction project, measured by the value Q_i of weighted aggregated optimality function (Table 3).

Ranking results are summarized, combining three mentioned aspects. In the current case study equal relative significances were assigned to all the groups of criteria. Summarized final results are as follows: Q_2 (0.614) > Q_3 (0.574) > Q_1 (0.564). Accordingly, when emphasising sustainability aspects and applying complex evaluation, the best ranked alternative is conversion of the industrial building into loft-type housing.

3.3 Additional comparison

To verify the results and to validate the proposed model, calculations applying several other MCDM methods with grey numbers [30, 33] are performed and the final rank using Rank Average Method is determined. The results are summarized in Table 4.

Table 4. Summarized ranking results

Alternatives a_i	a_1	a_2	a_3
WASPAS-G	3	1	2
SAW-G	3	1	2
WPM-G	3	1	2
TOPSIS-G	3	2	1
COPRAS-G	3	2	1
Average rank	3	1.4	1.6
Final rank	**3**	**1**	**2**

4. Conclusions

The research revealed that the old industrial buildings are highly attractive for investment using advanced evaluation techniques and technologies. Their redevelopment comprises a significant positive impact on the urban and architectural environment, as well as on the natural environment. If implemented, the selected engineering solutions could be friendly to the environment both in production and in operation.

The most advanced ICT and BIM techniques allow implementation of a project and afterwards a full lifetime management strategy of a real object, which is based on simulation of virtual prototypes of real objects in the static and dynamic environment

MCDM methods are proved to be highly suitable to support selection of the most effective decisions. BIM technique is suggested to be applied to support the decision-making selection process as reliable source of project information management and quality control.

The case study results applying the suggested information management and decision-making model confirmed that the conversion of the buildings is a leading trend in contemporary assets management. The priority order of the analysed redevelopment solutions was determined as follows: $a_2 \succ a_3 \succ a_1$.

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