Substitution of Material Solutions in the Operating Phase of a Building

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Abstract: During the operation of buildings, repairs, modernizations, adaptations, renovations, and reconstructions of parts of historic objects are performed. There is often the problem of using a different material or construction technology than was originally used, for a variety of reasons. For example, these are materials not currently manufactured, with necessary higher performance values (insulation, strength). The aim of the article was to analyze and evaluate the possibility of material substitution in repair works and to analyze the cause and effect analysis of its application in the context of different conditions. The article analyzes the causes and conditions of the substitution of materials in various stages of the exploitation phase of buildings, including historic buildings. A SWOT (Strengths, Weaknesses, Opportunities, Threats) matrix was developed for the phenomenon of material substitution during the operational phase. With aid from the DEMATEL (Decision Making Trial and Evaluation Laboratory) method, identification of cause–effect relationships regarding the issue of the possibility of applying the substitution of material solutions in building objects was carried out. The analysis carried out by the authors allows us to conclude that the use of substitution in the construction sector is justified and shows great opportunities in its implementation and development.

Keywords: substitution; operation and maintenance phase; cause–effect relationships; historical buildings

1. Introduction

The phenomenon of substitution is common in various fields of social and economic activity [1–4]. In the case of material economic activity, it is the mutual substitutability of goods with similar properties. The subject of the article is the substitution of constructional and material solutions in the implementation of construction projects, understood as a phenomenon consisting of replacing the designed object structure (element) with another one that meets the same or similar technical and functional requirements, as well as aesthetic requirements [5].

In construction, the application of substitution occurs throughout the life cycle of an object and addresses various issues. Both in the preparation phase, e.g., during choosing the location of a construction investment, variants of functions and/or construction, technology, as well as during the implementation of facilities and construction works, especially when the contractor is left with the choice of construction products. The selection and supply of construction sites with resources is related to the phenomenon of the substitution of suppliers and entire supply chains.

The exploitation phase of a building object is the longest period of its life cycle. However, the scope of construction works, at this stage, is not too large compared to the construction of the facility. Decisions related to undertaking repairs, including reconstruction, changes in the functions of rooms and facilities, and the choice of material solutions
of the structure, their repair, replacement, or renovation of finishing elements, etc., are
difficult and require many aspects to be taken into account.

Despite the phenomenon of substitution that has been present in construction projects
for years, there is a need to develop theoretical foundations and methods and tools to
support decision-making in construction practice. Analysis and selection of substitute
materials should consider the full life cycle of the object. They should also refer to current
socio-economic concepts such as sustainable development and the circular economy.

Substitution can significantly affect the quality, cost, and time of individual construc-
tion projects. It also has a broader multi-faceted impact on the delivery of construction in
environmental, economic, and social contexts. For example, the use of material substitution
may make it possible to meet a construction completion date in the event of a market
collapse or to purchase equally suitable but less expensive products. This may result
in improved user comfort or use of products whose manufacture and use do not result
in harmful emissions. This last example has a very large contribution to environmental
protection—the implementation of sustainable development principles.

In the presented article, the authors focus on the application of the possibility of
substituting construction products. It may be caused by the desire to use materials that
raise the standard of the facility and cost conditions, as well as limitations due to the
unavailability of original materials used during construction. The last aspect concerns, in
particular, the refurbishment of buildings entered in the register of monuments. The use
of replacement construction products in these types of buildings is a challenge, not only
because of the difficulty in selecting an appropriate substitute, but also because of meeting
the procedural requirements approved by the restorer. Thus, many factors and conditions
of different natures influence the selection of the best substitute under given conditions,
taking into account the consequences in terms of durability, strength, etc. during their
further use [6], and, therefore, on the life cycle costs of the facility.

The purpose of this paper is to analyze and evaluate the possibility of material substi-
tution in repair works and to analyze the cause and effect analysis of its application in the
context of various conditions. A division of the service life of a building was made in the
context of the execution of construction works, their contractors, and investors. Conditions
and factors occurring in the decision-making process of maintenance of the object in the
deteriorated condition, selection of works, and building materials were analyzed. Attention
is drawn to the possibility and necessity of material substitution in relation to historical
buildings. The developed SWOT matrix and its analysis allowed us to systematize factors
(conditions and limitations) of substitution in the exploitation phase and its influence on
the life cycle of buildings. The factors covering various substitution determinants, included
in the SWOT matrix, were used for identification of cause–effect relationships in the issue
of possibility to apply the substitution of material solutions in building objects. For this
purpose, the DEMATEL method was used.

2. Substitution of Construction Products in the Exploitation Phase of a Building Object

One of the activities aimed at caring for the environment is striving to extend the
life cycle. The products of the construction industry are one of the elements that allow
us to take care of this trend. Existing buildings are designed for many years, and thanks
to appropriate maintenance and refurbishment measures, they can survive many times
longer. One of the ways of extending the life cycle of building objects is to carry out a
refurbishment policy, during which it is necessary to take care of the proper selection of
material solutions.

Depending on the stage of exploitation under consideration, the participant of the
investment process, which may be the user, owner/investor, or property manager, will
make decisions in which sooner or later will meet the need, or even the necessity, to use
the substitution of construction products. Considering the wide market offer of construction
products, the decision-maker will have to consider many criteria before deciding to use a
product other than the originally built-in product.
Due to many different conditions, it is proposed in the research that the substitution of construction products in the operation phase should be considered by distinguishing its three stages/periods:

Substitution of construction products during the life of a building object is strictly connected with the division presented in Figure 1.

![Figure 1. Division of substitution during the lifetime of a building structure.](image)

During the warranty and guarantee period in a newly commissioned building, all necessary repairs should be carried out by the contractor who carried out this investment. Consequently, all costs associated with the construction work under consideration are not financially chargeable to the property owner. In the situation described above, due to the short period of time from putting the facility into use, construction products used for repairs and troubleshooting should still be available on the market.

The substitution of construction products during the warranty and guarantee period should result from a possible lack of availability of the original product at the moment of repairing the defect resulting from e.g., the necessity to wait too long for the construction product originally used in the facility, change of the manufacturer’s brand, completion of production of a specific construction product, a clear wish of the facility owner, or a change of e.g., fire safety regulations.

However, during the warranty and guarantee period, construction work may already occur that does not merely involve the removal and repair of faults. The owner of the property may decide to reconstruct, expand, or even change the use of a building that has just been put into use. In such a situation, the guarantee and warranty for the current scope of construction works is lost, and as a result, substitutes for the construction products originally used may be introduced.

The next stage of the operation of a building object, after the warranty period, which will usually last for several or even several dozen years, is a natural period during which substitution of construction products is a common phenomenon. It results from the natural wear and tear of a given element and the desire to replace it with other products that raise the standard of use, e.g., safety, convenience, aesthetics, comfort, and even fashion. After the expiry of the warranty and guarantee period, the construction products used for repairs are the responsibility of the property owners and to a large extent their choice is also dependent on the purchase price. In this phase of building operation, all factors that affect the price of the construction service (refurbishment, reconstruction, etc.) are crucial.

It can be stated that the investor, when determining the scope of planned works, in most cases initiates a tender procedure, which differs from the one used during the construction of a new facility only in the scope of planned works. The very stage of collecting offers, their consideration, and selection of a potential contractor is analogous to that of any new construction project under construction.

It is important to note that the selection of construction products during this phase is critical in terms of the life cycle of the facility [7]. The proper selection of these for
refurbishment and/or modernization works will have a significant impact on the extension or shortening of this phase of the life cycle as well as on costs [8–10]. Saving at the refurbishment stage may result in the necessity to perform another refurbishment quickly.

The use of substitutes for construction products of better quality and technical values may postpone the need for further refurbishment as well as reduce maintenance costs and also raise the standard of the facility.

Figure 2 presents the change of utility values of a building object in its life cycle, which is connected with two main processes, i.e., constant decrease of utility properties—from the moment of putting the object into use (curve b) and simultaneous increase of the object users’ requirements while taking into account changes in regulations and standards (curve a*). The drop in the value of curve b is caused by the wear and tear of individual building elements during the operation phase. The continuous line is the performance assessment at the moment the building is put into operation. It was assumed that the building was designed and constructed in accordance with the relevant standards (Eurocodes) with the application of the required supervision procedures and control throughout the construction process. The dashed straight line Z specifies the minimum level of utility requirements that a building should meet. If the assessment of performance is below the Z level, further use of the object is unacceptable.

![Figure 2. Schematic diagram of the increase in building performance requirements (a-curve) and changes in technical condition due to aging and renovation during the building’s service life (b-curve) [11,12].](image)

The decrease in the value of curve b is caused by the wear and tear of individual building elements during the exploitation phase. We can observe “jumps” on it, i.e., an increase in the usable value of the object as a result of repairs and renovations—points B1 and B2—and modernization—point D [12]. Modernization is caused not only by the increase of users’ requirements but also by the increase of requirements regarding the object’s features as a result of stricter legal regulations (e.g., regarding fire protection).

Construction objects are characterized by a long service life when properly operated. Very often they perform a completely different function than those for which they were designed. The durability of their construction exceeds the often assumed periods [13,14]. We have many examples in the world of such age-old buildings and structures. In Europe, in particular, for many years there has been a desire to take care of the historical substance, objects of historical, cultural, and religious significance that bear witness to past eras. Many
of the objects among those existing in the building stock, that due to their exceptional value, are entered in the register of monuments kept by the relevant governmental administration bodies. There is no specific time after which the building is considered a monument. The Act on the Protection and Care of Historical Monuments states that any building which is important for history and science can become a monument, and thus should be preserved [15]. It can also be a building built in the 1950s or 1960s if it presents features characteristic for the architecture of a given period and can be important for its history. Buildings entered in the register of monuments are subject to the Act on the Protection and Care of Historical Monuments [16] and all activities related to the use and in particular their maintenance in a proper technical condition and standard are subject to the supervision of the conservator. Thus, in the phase of exploitation of buildings, the period of their functioning as a monument should be distinguished for a group of exceptional objects.

Substitution starts to appear much more often in the case of buildings already in use for a longer period of time [17–21]. Among the exploited properties, we can observe a certain phenomenon, in which the trend is manifested by the growing deficiencies in the documentation of the exploitation of the building with its age. For example, the documentation of mass-produced buildings built in the 1970s and 1980s in large panel technology is often incomplete and inconsistent. Therefore, owners often look for construction products similar to the original ones while carrying out renovation works, usually guided by the criterion of aesthetics and price. In this case, someone else is also responsible for financing the work on the facility. In cooperative buildings or those owned by housing communities, the costs of all repairs and renovations is borne by the property owners. Most often this is done through the so-called “renovation fund”. Such works are very often performed in the order of “from the most urgent”, unfortunately in many cases without taking into account the durability of the construction products used for this purpose.

Moreover, one of the major problems of substitution is the choice of substitute material. During the design phase, the architect is almost free to choose a replacement material. In contrast, there are many more factors to consider during the renovation phase. Thanks to advances in material engineering, manufacturers offer a large selection of substitution products with different properties. There is a need to select criteria to evaluate possible alternate materials and make a decision. This is done by multi-criteria analysis using different methods [22]. Among the adopted criteria, the important ones are those that take into account the principles of sustainable development. Therefore, ecological materials, modern technologies or modernization of traditional ones with addition of raw materials from different branches of economy (tea to brick) are being sought.

Two types of approach to substitution can be observed. The first, in a more general sense, is an attempt to:

- produce new materials and building elements capable of performing the appropriate function in the construction of a building. Improve their physical, chemical, etc. properties and usability (durability, aesthetics, usability, operation, etc.), thanks to the development of materials engineering, using the achievements of science, nanotechnology, etc. [23–26]. They can be used interchangeably with traditional materials (instead of clay bricks, e.g., cellular concrete).

The second, however, related to the idea of sustainable development through:

- development and use of materials and elements of the structure of a building and its equipment in building installations which minimize energy consumption (energy efficient) [27–29];
- production of raw and building materials using wastes (as additives e.g., to cement and aggregates or entirely made from waste) [30–33].

The second approach to substitution is a partial restriction on the choice of a substitute by, for example, an architect, developer, or user by placing a condition (of an aesthetic, logistical, etc. nature). This situation relates to a specific building or material solution [34,35]. Here also the selection can be made in terms of one or more optimization criteria [36]. The
criteria are based on the individual requirements of the user, the investor or on current social and economic concepts: sustainable development, circular economy [37]. Applying material substitution, it is useful to have knowledge about the determinants of its use, the cause–effect relationships of the factors that have an impact on its use. Such research and results are presented in Section 4 of the article.

3. Substitution in Historical Buildings

It should be noted that in most European countries it is obligatory to replace the materials used in historic buildings with the same ones that were used originally. In Poland, however, the law allows the use of substitutes [16] depending on various conditions.

Factors that affect the possibility of using construction product substitutes are defined in the so-called conservation program, which is developed for each renovation of an object entered in the register of monuments. Each proposed substitute for a construction product must be prepared in the form of a sample and accepted by the Conservator.

Positive aspects of the application of construction product substitution in the renovation of buildings entered in the register of monuments are the factors that primarily enable the refurbishment. Historic sites were built in different construction realities, at a time when available building products were based on natural resources (e.g., stone, rock, clay) and the technology to produce them was simpler. It was common practice to import construction products from other areas of Europe. Even today it is costly and environmentally unfriendly and, due to the environmental protection of certain areas, exploitation is prohibited. However, it is worth considering the use of a substitute material and conducting an analysis of the impact of using such a solution on social, environmental, and economic factors [38–41].

Ownership of the most valuable objects entered in the register of monuments is mostly in the hands of the State or various institutions such as the churches. It should be remembered that the number of facilities under consideration is large and the possibilities of financing renovations are limited, hence the price will always be an important component of planning a refurbishment. The use of original construction products in one object may lead to abandonment or postponement of the renovation in other objects. Such a situation may lead to degradation of the remaining buildings and, consequently, increase the costs of renovations that are planned in them. Therefore, the introduction of substitutes for construction products in historic buildings, which give positive aesthetic and visual values and are less of a financial burden, gives the opportunity to conduct a more effective and larger-scale renovation policy.

In the case of the described refurbishments, a significant price-creating factor is also the time of completion. It is obvious that a longer period of renovation of one object can postpone the start of renovation in another object, which also requires this renovation. Substitution of construction products may increase the pace of renovation works in connection with, among others, less complicated technology of conducting works, faster pace of assembly of built-in elements, and the possibility of conducting works in less favorable weather conditions. Reducing the duration of the renovation gives further savings, thanks to which it is possible to predict that the renovation of a monumental object (the process of renovation of an object entered in the register of monuments takes a very long time because not all the necessary construction works can be predicted at the stage of designing the renovation) will be completed within the assumed time.

Construction products used in historic buildings have often survived years or even centuries. Thus, these are durable products that have been subject to gradual degradation over the years due to lack of refurbishment or minor damage, which has increased the impact zone from year to year [42,43]. The weakness of the construction product substitutes may be their durability and resistance to weather conditions in comparison with primary products and other influences e.g., related to the intensity of car exhaust or air pollution [44]. Renovations of buildings included in the register of monuments should be carried out by companies specializing in this type of construction works. Due to the specific nature of
renovation work in historic buildings, the contractor may encounter problems at each stage of the work that are unusual for newly erected buildings.

Substitutes of construction products used in the renovation of historic buildings give a wide range of possibilities. Substitutes can be manufactured from recycled, environmentally-friendly materials and produced by local entrepreneurs [7,45]. The current technology of conducting construction works and the variety of construction products makes it possible to carry out a renovation of basically any building, including historic buildings.

In the current market situation, the cost and time of implementation are critical in any type of construction project. In the case of renovations of objects entered in the register of monuments, the specificity of the conducted construction works and a certain unpredictability of additional construction works, which may appear at each stage of the renovation, are still imposed.

The authors met with an opinion that a historic object that has undergone renovation with the use of construction product substitutes loses its historical value and should no longer be treated as a monument. The basic issue to consider in such a situation is the possibility of renovation.

In old, historic buildings, especially those protected by law (in Poland the register of historic monuments), the use of substitution of materials has a long history. There is an extensive literature in this area, including concepts of substitution principles, developed and proven methodologies for design, testing, analysis, and selection of substitutes [46–48].

4. Evaluation of the Possibility of Using Material Substitution in the Maintenance of Buildings

Preceding the decision to use substitution, the authors suggest performing an assessment and identifying key factors that influence the effectiveness of its use. On the basis of the presented conditions and factors influencing the application of substitution in construction objects in the exploitation phase, a SWOT (Strengths, Weaknesses, Opportunities, Threats) matrix was developed (see Table 1). It contains factors that constitute strengths and weaknesses of the substitution phenomenon and opportunities and threats in its application.

| Positive | Negative |
|----------|----------|
| **Strengths** | **Weaknesses** |
| **Inside** | | |
| 1.1. possibility of refurbishment, | 2.1. faster degradation of the object’s substance by inappropriate selection of built products, |
| 1.2. lower price of the renovation, | 2.2. involvement in the work of specialized companies, |
| 1.3. faster pace of construction works (less complicated technology), | 2.3. conducting works by experienced supervision, |
| 1.4. to achieve the desired visual effect, | 2.4. investment revaluation, |
| 1.5. replacement of products that are no longer found in the market, | 2.5. possible lack of a proposed substitute in a previously approved solution |
| 1.6. shortening of supply chains | | |

| **Outside** | **Threats** |
| ----------- | ----------- |
| 3.1. market (access and development) of modern construction products | 4.1. loss of authenticity and historical value and object |
| 3.2. recycled products | 4.2. specific requirements for carrying out works, especially renovations during adverse weather conditions, |
| 3.3. products more environmentally friendly, | 4.3. lack of competent professionals, inspectors, conservators, |
| 3.4. establishing cooperation with local entrepreneurs, | 4.4. lack of legal regulations concerning the applied solutions |
| 3.5. revitalization of degraded areas under conservation care | |
The analysis of the matrix, in particular the comparison of factors from different fields of the matrix gives an opportunity to determine the type of a possible general strategy in substitution activity, as well as detailed strategies in organizations dealing with the management of building real estate, including historic buildings.

If a strategy is established, reference should be made to a specific object.

On the basis of the analysis of information from the presented SWOT matrix, conclusions can be drawn with regard to the possibilities for developing material substitution in the construction industry. Undoubtedly, in the situation of emerging new and modern technologies, more and more diversified offers of the manufacturers’ market allows for flexible and quick adaptation of investors to the dynamics of social and economic changes, especially for such long-lasting products as building structures. Undoubtedly, there is an advantage to the benefits of substitution in various aspects of the investment and construction process, both in terms of execution and ancillary activities, including logistics. Out of the four presented threats, two factors concern historic buildings, and one needs to be supplemented in legal regulations. The fourth one related to the requirements of relevant competences requires the support of the educational system.

The information contained in the presented SWOT matrix can be used in two ways. It can be used to analyze and generally evaluate the development of a certain phenomenon. It can also be used in the strategic analysis of an individual specific enterprise, company, or system.

This paper will use the data from the SWOT matrix to assess the overall feasibility of using substitution in building repair work (Section 5). The factors collected in the SWOT matrix can be used to establish cause–effect relationships between them. Identifying the causal chain will allow us to identify those factors that have the greatest impact on the process of substitution.

For an individual facility, on the other hand, this analysis will determine whether the planned substitution will have a more positive or negative impact on the renovated facility. It will also allow the investor to look at all the pros and cons of using substitution and assist him in making a final decision on the renovation policy on the chosen facility.

5. Cause-and-Effect Analysis of the Use of Substitution

5.1. Research Methodology

To identify cause–effect relationships in the issue of possible substitution of material solutions of buildings the authors propose to use the DEMATEL method [49–52]. When analyzing a multi-factor problem, a multi-criteria analysis is used to evaluate the problem using different methods that allow ranking of solutions. On the other hand, the DEMATEL method chosen by the authors also enables a cause-and-effect analysis of the phenomenon under study.

The computational flow is as follows:

1. Determining a set of influence factors, in the proposed study based on the SWOT matrix (Figure 3);
2. Development of a direct influence graph, according to the DEMATEL method, which allows us to express the targeted influence of the considered factors on each other, in a cause-and-effect context. A scale with a parameter value of N = 3 (where: 0—no influence, 1—weak influence, 2—influence, 3—strong influence) was used to assess the “strength” of the influence of each factor. The values of the direct influence relationships within each pair of factors were determined based on the evaluations of the expert group and they were calculated using fuzzy logic;
3. Based on the relationships determined with the graph, a matrix of direct mutual influence of factors on each other $A_D$ was created (Figure 4);
4. Determination of the normalized direct influence matrix $A'_D$, which contains all parameters that take values that are in the range $[0, 1]$ (Table 2). The normalizing number ($n$) is taken as the largest of the sum of the rows or columns of the matrix $A_D$:

$$A'_D = \frac{A_D}{n},$$

$$n = \max \left\{ \sum_{i=1}^{n} a_{ij}; \sum_{j=1}^{n} a_{ij} \right\},$$

5. It is also possible to develop an indirect impact matrix $\Delta T$:

$$\Delta T = A'^{2}_D (I - A'_D),$$

6. Determination of the total influence matrix $T$ (Table 3):

$$T = A'_D (I - A'_D),$$

7. On the basis of the above matrices, the determination of the indices of position and relationship, respectively, which express in turn: $s^+$ — tells about the role of a given factor in the process of determining the structure of links between objects, while $s^-$ — expresses the total influence of a given factor on the others. These values are determined according to the formulas (Table 4):

$$s^+ = \sum_{j=1}^{n} t_{ij} + \sum_{j=1}^{n} t_{ji} = R_{Ti} + C_{Ti},$$

$$s^- = \sum_{j=1}^{n} t_{ij} - \sum_{j=1}^{n} t_{ji} = R_{Ti} - C_{Ti},$$

When these values are plotted on a graphical representation, it is easy to see which factors have the greatest influence on the others and to determine which are the causes and which are the effects of the actions taken (Figure 5).

8. Finally, the net impact value is also determined, which tells the factor that has the greatest impact on the others considering both the causal and effect nature (Table 4):

$$netto = s^+ + s^-$$

Table 2. The fragment of normalized direct influence matrix $A'_D$.

|     | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 2.1 |
|-----|-----|-----|-----|-----|-----|-----|-----|
| 1.1 | -0.0156 | -0.0017 | 0.0000 | 0.0313 | 0.0000 | 0.0000 | -0.0035 |
| 1.2 | 0.1250 | 0.0000 | 0.0000 | -0.0052 | 0.0000 | 0.0000 | 0.0833 |
| 1.3 | 0.0729 | 0.0833 | 0.0000 | -0.0035 | 0.0000 | 0.0000 | -0.0069 |
| 1.4 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 1.5 | 0.1128 | 0.0330 | 0.0816 | 0.0781 | -0.0017 | -0.0035 | -0.0052 |
|     | ... | ... | ... | ... | ... | ... | ... |
Table 3. Total influence matrix T (fragment).

|   | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 2.1 |
|---|-----|-----|-----|-----|-----|-----|-----|
| 1.1 | 0.0000 | 0.0000 | 0.0000 | 0.0417 | 0.0000 | 0.0000 | 0.0000 |
| 1.2 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0833 |
| 1.3 | 0.0833 | 0.0833 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 1.4 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 1.5 | 0.1250 | 0.0833 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

Table 4. Summary of DEMATEL analysis results.

| Criterion i | $R_{Ti}$ | $C_{Ti}$ | $s^+$ | $s^−$ | Netto |
|-------------|----------|----------|-------|-------|-------|
| 1.1         | 0.2830   | 0.6042   | 0.8872| −0.3212| 0.5660|
| 1.2         | 0.2396   | 0.4288   | 0.6684| −0.1892| 0.4792|
| 1.3         | 0.1146   | 0.1198   | 0.2344| −0.0052| 0.2292|
| 1.4         | 0.5243   | 0.0399   | 0.5642| 0.4844 | 1.0486|
| 1.5         | 0.1198   | 0.1198   | 0.2396| −0.1701| 0.2396|
| 2.1         | 0.0799   | 0.1708   | 0.2507| −0.1910| 0.1181|
| 2.2         | 0.1181   | 0.1632   | 0.2813| −0.0451| 0.2761|
| 2.3         | 0.1198   | 0.0330   | 0.1528| 0.0868  | 0.2396|
| 2.4         | 0.0000   | 0.0000   | 0.0000| 0.0000  | 0.0000|
| 2.5         | 0.0000   | 0.1163   | 0.1163| −0.1163| 0.0000|
| 3.1         | 0.4757   | 0.0000   | 0.4757| 0.4757  | 0.9514|
| 3.2         | 0.2865   | 0.0122   | 0.2986| 0.2743  | 0.5729|
| 3.3         | 0.3038   | 0.0399   | 0.3438| 0.2639  | 0.6076|
| 3.4         | 0.0347   | 0.0399   | 0.0747| −0.0052| 0.0694|
| 3.5         | 0.1563   | 0.0365   | 0.1927| 0.1198  | 0.3125|
| 4.1         | 0.0365   | 0.7743   | 0.8108| −0.7378| 0.0729|
| 4.2         | 0.1927   | 0.1632   | 0.3559| 0.0295  | 0.3854|
| 4.3         | 0.1094   | 0.0000   | 0.1094| 0.1094  | 0.2188|
| 4.4         | 0.2153   | 0.1215   | 0.3368| 0.0938  | 0.4306|

Figure 3. Direct influence graph—expert evaluation results.
Table 5.2. Study Results and Its Analysis

In supporting the decision to use substitution to examine the cause and effect relationships, all the factors summarized in the SWOT matrix were considered. These factors, as in the case of the SWOT matrix, were divided into the same four groups. To simplify the recording of the factors in further analysis with the help of the DEMATEL method, only the number from the SWOT table is marked (see Table 1).

The factors identified during the SWOT analysis are subjected to an assessment of the strength of their impact on each other.

For the analyzed issue—application of substitution, e.g., in repair works, the form of direct influence graph is presented in Figure 3. The intensity of relationships was coded using different hatchings of arc lines.

**Figure 4.** The matrix of direct effects of factors on each other.

**Figure 5.** Graphical interpretation of DEMATEL results.
Based on the relationships illustrated above, a direct influence matrix $A_D$ was created (step 3).

Table 2 shows fragment of element values of the normalized matrix (step 4):

Next, based on Equation (3), the matrix of total relations $T$ was determined:

A summary of the values to build an illustration of the causal nature is shown in Table 4 (step 7).

The analysis was performed by using summative, linear aggregation of the values of the position and relationship indicators ($s^+$ and $s^−$). The calculations in general are expressed in the graph shown in Figure 5, which shows the values of the position and relationship indicators. Based on the aggregated values of the item index, it was found that the greatest role in determining the nature of the factors is played by: 3.1 (market-access and development of modern construction products) and 1.5 (replacement of products no longer manufactured).

Factors 3.2 (recycled products) and 3.3 (more environmentally friendly products) have slightly less influence. The clearly positive values of the relationship index for these factors indicate their causal character.

Almost half of the analyzed factors show a negative value of the relationship index, hence they should be treated as possible effects of the causes.

Of the factors with a negative relationship index value, a significantly outstanding negative value was obtained by 4.1 (loss of authenticity and historical value and object), which represents the largest negative possible effect of using substitution.

Factors with a positive sign but close to the zero value can be treated as elements of a mixed nature, partly causal, partly effectual, but both as causes and effects of far less importance.

The situation is different if we look at the values of the factors they obtain in the position axis (Figure 5). Factors with above average values of the item index testify to their leading role in determining the nature of individual factors. Among the prominent factors of the position indicator are 1.1 (possibility of renovation), 4.1 (loss of authenticity and historical value of the object), 1.2 (lower price of renovation), 1.5 (replacement of products no longer manufactured), and 3.1 (market-access and development of modern construction products). Again, as far as the others are concerned, they have far less active participation in the process of identifying the role of factors.

The aggregated values of the relation index allowed for distinguishing three groups of factors: key, average and insignificant for shaping the renovation policy. In particular, the key factors as reasons for decision-making turned out to be: 3.1, 1.5. Key factors as reasons for taking the group of average significant factors form: 3.2 i 3.3. The other factors can be considered by far the least important.

The possible impacts of the decision are definitely influenced by factor 4.1, which reflects the fear of losing the authenticity of the historic substance, as well as 1.1, which represents the opportunity for renovation. The fear of loss of authenticity should be the starting point in selecting the right, in this case the closest substitution to the original. The effect of being able to renovate is a decisive advantage of substitution and can often be the only solution to improve the technical condition of an object and extend its life cycle.

6. Summary

Substitution of construction products is a common phenomenon in the construction industry at every stage of a building’s life cycle. Moreover, sometimes the use of substitution may be the only feasible solution to save a facility. In a wider context, it can have a great impact on the implementation of the principles of sustainability and circular economy in the maintenance of building stock.

The conducted observations show that during the warranty and guarantee period in newly constructed buildings, the substitution of construction products is much lower than in the next period of the facility’s operation. The phenomenon of substitution, however, is
often encountered in the long-term perspective of facility operation, especially during all repair and overhaul works.

One of the ways of extending the life cycle of buildings is a proper renovation policy, which through proper selection of material solutions will ensure longer durability of components and the entire facility.

A special case is the substitution in the renovation works of objects entered in the register of monuments, which gives the possibility to protect the historic substance while maintaining the structural and aesthetic values.

Product substitution, which is often cheaper than the original, may also allow for a wider range of renovations, which directly contributes to improving the technical and functional condition of the object and thus allows for extending its life cycle.

The SWOT analysis conducted by the authors allows us to conclude that substitution in the construction industry is justified and that there are great opportunities for its implementation and development. A detailed analysis of the SWOT matrix factors, using the DEMATEL method, allowed for an overall assessment of substitution possibilities with the determination of the cause–effect relationship of factors from particular groups characterizing the strengths and weaknesses of substitution as well as the opportunities and threats. Undoubtedly, the use of substitute materials, especially in historic buildings, will result in a decrease in their authenticity, but will ultimately restore them to safe operation and in other buildings allow for an extended life cycle.

Despite the possibility of product substitution thanks to materials engineering and technology development, the use of substitution should not be approached uncritically. The authors recommend a case-by-case approach, conducting a comprehensive analysis and making decisions based on, among other things, the tools proposed in the article and evaluating the cause-and-effect relationships that will occur when substitution is applied.

The above comment also applies to using a different approach to material substitution in historic buildings. The decision whether or not to use substitution and the freedom to choose substitution solutions are influenced by the conservation concepts and legal regulations of the respective country or type of object.

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References

1. Linczowski, K.; Sobotka, A. Relations between substitution in technological processes and construction supply logistics. Logistics 2014, 6, 9816–9825.
2. Gustavsson, L.; Pingoud, K.; Sathre, R. Carbon dioxide balance of wood substitution: Comparing concrete- and wood-framed buildings. Mitig. Adapt. Strat. Glob. Chang. 2006, 11, 667–691. [CrossRef]
3. Wadr, H.J. The Use of Substitute Materials on Historic Building Exteriors. 1988. Available online: http://www.nps.gov/tps/how-to-preserve/briefs/16-substitute-materials.htm#top (accessed on 14 February 2021).
4. New Zealand Government, Ministry of Business Innovation & Employment. Quick Guide to Product Substitution; New Zealand Government: Wellington, New Zealand, 2004.
5. Linczowski, K.; Sobotka, A. Analysis of logistics for construction site supply with reinforcing steel. *Tech. Trans. Civ. Eng.* 2014, 6, 225–232.

6. Arendalski, J. *Durability and Reliability of Residential Buildings*; Arkady: Warsaw, Poland, 1978.

7. Petersen, A.K.; Solberg, B. Environmental and economic impacts of substitution between wood products and alternative materials: A review of micro-level analyses from Norway and Sweden. *For. Policy Econ.* 2005, 3, 249–259. [CrossRef]

8. Fregonara, E.; Patono, S. A sustainability indicator for building projects in presence of risk/uncertainty over time: A research experience. *AESTIMUM* 2018, 19, 173–205.

9. Grzył, B.; Apollo, M.; Miszewska-Urbańska, E.; Kristowskim, A. Object operation management in terms of life cycle costs. *Acta Sci. Pol. Built. Eng.* 2017, 16, 85–89.

10. Plebankiewicz, E.; Meszek, W.; Zima, K.; Wieczorek, D. Probabilistic and fuzzy approaches for estimating the life cycle costs of buildings under conditions of exposure to risk. *Sustainability* 2020, 12, 2504. [CrossRef]

11. Orłowski, Z.; Szkleniak, N. Analysis of the building value in use as a function of time. *Tech. Trans.* 2010, 6, 303–312.

12. Radziejowska, A. The Method of Assessing the Social Performance of Residential Buildings in the Aspect of Sustainable Construction. Ph.D. Thesis, AGH, Cracow, Poland, 2018.

13. Economakis, R. *Durability in Construction: Traditions and Sustainability in 21st Century Architecture*; Papadakis Publisher: Winterbourne, Berkshire, UK, 2015; ISBN-13: 978-1906506551.

14. Bai, J. Durability of sustainable construction materials. *Sustain. Constr. Mater.* 2016, 38, 397–414.

15. Gmiter, M. *Guide to the Investment Process in Historic Buildings*; Presscom Sp. Z o.o.: Poland, Wrocław, 2018.

16. Act on the Protection and Care of Historical Monuments, Old Monuments Law (Ustawa, o Ochronie Zabytków; Opiece Nad Zabytkami) of 23 July 2003, with Later Changes; Journal of Laws: 2014; pos. 1446. Available online: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20031621568/U/D20031568LJ.pdf (accessed on 16 February 2021).

17. Technical Preservation Services. *Evaluating Substitute Materials in Historic Buildings*; Historic Preservation Tax Incentives Programme: Washington, DC, USA, 2007.

18. Cluver, J.H. *No Substitute: Inexpensive and Maintenance Free or Short Sighted and Maintenance Proof: How Do Substitute Materials Stack Up in the Long Run?* Labine’s Period Homes: Boulder, CO, USA, 2005; pp. 12–16.

19. Dierickx, M.B. Substitute materials for wooden buildings: The system or the artifact? *APT Bull.* 1986, 18, 4–5. [CrossRef]

20. Capen, J. Using substitute materials in a historic district. *Hill Rag* 2008, 5, 134–135.

21. S & D Design Guidelines for Landmark. *Guidelines for Preserving Historic Buildings—Alterations to Landmark Structures and Contributing Structures in Historic Districts*; S & D Design Guidelines for Landmark: Denver, CO, USA, 2016.

22. Zavadskas, E.K.; Turkis, Z.; Tamouaitiene, J. Selection of construction enterprises management strategy based on the SWOT and multi-criteria analysis. *Arch. Civ. Mech. Eng.* 2011, 11, 1063–1082. [CrossRef]

23. Nawar, A.H. Nano-technologies and nano-materials for civil engineering construction works applications. *Mater. Today Proc.* 2020. [CrossRef]

24. Razakhanova, F.M. Issues concerning import substitution of building materials in the construction market. *Vestn. Dagest. Gos. Teh. Univ. Teh. Nauk.* 2018, 44, 223–233. [CrossRef]

25. Li, H.; Xu, B. *Advanced Building Materials and Structural Engineering*; Advanced Materials Research; Trans Tech Publications Ltd.: Zurich, Switzerland, 2012; Volume 461.

26. Enriquez, E.; Torres-Carrasco, M.; Cabrera, M.; Muñoz, D.; Fernández, J. Towards more sustainable building based on modified Portland cements through partial substitution by engineered feldspars. *Constr. Build. Mater.* 2020. [CrossRef]

27. Piccardo, C.; Dodoo, A.; Gustavsson, L.; Tettey, U. Retrofitting with different building materials: Life-cycle primary energy implications. *Energy* 2020, 19, 5–10. [CrossRef]

28. Blomqvist, S.; La Fleur, L.; Amiri, S.; Rohdin, P.; Odlund, L. The impact on system performance when renovating a multifamily building stock in a district heated region. *Sustainability* 2019, 11, 2199. [CrossRef]

29. Rubio-Cintas, M.D.; Parron-Rubio, M.E.; Perez-Garcia, F.; Ribeiro, A.B.; Oliveira, M.J. Influence of steel slag type on concrete shrinkage. *Sustainability* 2021, 13, 214.

30. Bouasria, M.; Khadraroui, F.; Benzama, M.-H.; Touati, K.; Chateignier, D.; Gascoin, S.; Pralong, V.; Orberger, B.; Babouri, L.; El Mendili, Y. Partial substitution of cement by the association of Ferronickel slags and *Crepidula fornicata* shells. *J. Build. Eng.* 2021, 4, 103. [CrossRef]

31. Chen, W.; Li, Y.; Chen, S.; Zheng, C. Properties and economics evaluation of utilization of oil shale waste as an alternative environmentally-friendly building materials in pavement engineering. *Constr. Build. Mater.* 2020. [CrossRef]

32. Patel, D.; Shrivastava, R.; Tiwari, R.; Yadav, R. Properties of cement mortar in substitution with waste fine glass powder and environmental impact study. *J. Build. Eng.* 2020. [CrossRef]

33. Raheem, A.A.; Ikotun, B.D. Incorporation of agricultural residues as partial substitution for cement in concrete and mortar. *J. Build. Eng.* 2020. [CrossRef]

34. Hafner, A.; Schäfer, S. Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level. *J. Clean. Prod.* 2017, 167, 630–642. [CrossRef]

35. D’Amico, B.; Pomponi, F.; Hart, J. Global potential for material substitution in building construction: The case of cross laminated timber. *J. Clean. Prod.* 2021, 7, 279. [CrossRef]
36. Vachris, J. Asbestos substitution serviceability of new materials. In Proceedings of the Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Conference, Cincinnati, OH, USA, 26–28 October 1999.

37. Omer, M.A.; Noguchi, T. A conceptual framework for understanding the contribution of building materials in the achievement of Sustainable Development Goals (SDGs). Elsevier Sustain. Cities Soc. 2020, 52, 244–302. [CrossRef]

38. Van Domelen, S.K. The Choice Is Yours: Considerations & Methods for the Evaluation & Selection of Substitute Materials for Historic Preservation. Ph.D. Thesis, University of Pennsylvania, Philadelphia, PA, USA, 2009. Available online: http://repository.upenn.edu/hp_theses (accessed on 14 February 2021).

39. Liu, L.; Li, H.; Lazzaretto, A.; Manente, G.; Tong, C.; Liu, Q.; Li, N. The development history and prospects of biomass-based insulation materials for buildings. Renew. Sustain. Energy Rev. 2017, 69, 912–932. [CrossRef]

40. Iucolano, F.; Boccarusso, L.; Langella, A. Hemp as eco-friendly substitute of glass fibres for gypsum reinforcement: Impact and flexural behaviour. Compos. Part B Eng. 2019, 175, 25. [CrossRef]

41. Mathur, V. Composite materials from local resources. Constr. Build. Mater. 2006, 20, 470–477. [CrossRef]

42. Myers, J.; Aluminum and Vinyl Siding on Historic Buildings. The Appropriateness of Substitute Materials for Resurfacing Historic Wood Frame Buildings. 1984. Available online: https://www.nps.gov/TPS/how-to-preserve/briefs/8-aluminum-vinyl-siding.htm (accessed on 14 February 2021).

43. Nowogońska, B. Value of technical wear and costs of restoring performance characteristics to residential buildings. Buildings 2020, 10, 9. [CrossRef]

44. Demir, I. An investigation on the production of construction brick with processed waste tea. Build. Environ. 2006, 9, 1274–1278. [CrossRef]

45. Teha, S.H.; Wiedmann, T.; Schinabeck, J.; Moorea, S. Replacement scenarios for construction materials based on economy-wide hybrid LCA. Procedia Eng. 2017, 180, 179–189. [CrossRef]

46. Friedman, D. Historical Building Construction: Design, Materials, and Technology; W.W. Norton & Company: New York, NY, USA, 1995.

47. Fisher, T. The sincerest form of flattery. Progress. Archit. 1985, 85, 118–123.

48. Brownell, B. Transmaterial: A Catalog of Materials that Redefine our Physical Environment; Princeton Architectural: New York, NY, USA, 2006; Volume 6.

49. Dytczak, M.; Ginda, G.; Gotowala, B.; Szklenik, N. Application potential of Dematel method and its extensions for analysis of decision problems in civil engineering. Bud. Inżynieria Sr. 2011, 2, 235–240.

50. Sheng-Li, S.; Xiao-Yue, Y.; Hu-Chen, L.; Ping, Z. Dematel technique: A systematic review of the state-of-the-art literature on methodologies and applications. Math. Probl. Eng. 2018, 23, 1–33.

51. Jiunn, I.S.; Hsin-Hung, W.; Kuan-Kai, H. A Dematel method in identifying key success factors of hospital service quality. Knowl. Based Syst. 2010, 23, 277–282.

52. Kijewska, K.; Torbacki, W.; Iwan, S. Application of AHP and Dematel methods in choosing and analysing the measures for the distribution of goods in Szczecin region. Sustainability 2018, 10, 2365. [CrossRef]