Decision support systems in building construction – an Axiomatic Design approach

Carmen Marcher¹², Erwin Rauch¹, Andrea Giusti² and Dominik T Matt¹²

¹ Free University of Bolzano, Faculty of Science and Technology, Piazza Università 5, 39100 Bolzano, Italy
² Fraunhofer Research Italia s.c.a.r.l., Via A. Volta 13 A, 39100 Bolzano, Italy

E-mail: carmen.marcher@natec.unibz.it

Abstract. The introduction of Industry 4.0 leads to new decision-making scenarios in the construction industry. The construction sector still hesitates to adopt emerging technologies and many construction companies require support in the field of digitalisation and automation of processes. One way to support this sector is the use of decision support systems that perform a careful assessment of the feasibility for replacing traditional systems with automated ones. However, the design and the development of decision support systems is a complex and time-consuming task. In this work we apply Axiomatic Design to define design guidelines for the development of decision support systems in construction equipment selection. The needs of the construction industry for decision support in these scenarios are derived from existing literature in the field of construction and the key characteristic of decision-theoretic expert systems. These needs are analysed and translated into functional requirements. Then, through a mapping and decomposition process, the design solutions for the development of a decision support system are deduced. Functional requirements and design solutions are transformed into design guidelines that support the systematic development and implementation of decision support systems for the construction phase of a building.

1. Introduction

While the industrial sector is radically changing with the increasing adoption of Industry 4.0 [1], the construction sector still hesitates to adopt emerging technologies. To overcome this gap, it is necessary to support the construction sector in the field of digitalisation and automation [2]. One way to assist this sector in meeting this challenge is the development and employment of systems that support decision makers in the choice of the most appropriate technological solution to be adopted on the construction site [3]. Decision support systems (DSS) are widely employed interactive computer-based systems that assist users in decision making [4], and the need for adopting such systems in construction is constantly increasing [5]. In recent years, the interest towards the development and the adoption of DSS in construction has grown substantially, and most of the DSS are proposed for the construction phase [6]. Although formal methods for decision making are the most employed methods within DSS in construction [5,6], approaches that account for uncertainty are preferred by decision makers as they reflect reality more accurately [7]. In this work, we apply Axiomatic Design (AD) [8] to define a design guideline for developing and implementing DSS for equipment selection in the construction phase of a building. The development of the guideline is based on the fundamental characteristics of decision theoretic expert systems and an analysis of relevant literature in the field of construction equipment selection. The contribution of this paper is to structure a complex development...
and implementation process by dividing the process into small and manageable development and implementation packages.

This work is structured as follows: In Section 2 we present the related background. In Section 3 we describe the application of the AD-based design approach and the resulting design guidelines. In Section 4 we draw the conclusions.

2. Background

2.1. Bayesian decision theory and decision-theoretic expert systems

DSS based on probabilistic networks are called decision-theoretic expert systems. Bayesian networks are probabilistic networks that allow reasoning under uncertainty and the representation of uncertain knowledge. Bayesian networks that incorporate also actions and utilities are called Bayesian decision networks or influence diagrams [9]. They allow one to represent and describe decision problems both quantitatively and qualitatively [10], and evaluate preferences and the probability that a specific outcome occurs. They follow the Principle of Maximum Expected Utility (MEU) [11] to compute the action that yields the highest expected utility [9,10]. In summary, decision-theoretic expert systems perform rational decision making based on available evidence and preferences within a given area of expertise [9] by means of probabilistic networks [10]. The applicability of Bayesian decision theory for developing and implementing DSS in the field of construction equipment selection has been shown by means of an exemplary case study that emulates the choice between a conventional scaffold and a mast climber platform for façade installation [3].

2.2. Literature survey on DSS for construction equipment selection

The relevant literature was mapped by performing a manual search of articles and conference papers on Elsevier’s database Scopus, a peer-review database in the field of engineering sciences. The search is limited to English articles in the publication period from 2016 to November 2020, and to articles that are part of the subject areas Engineering or Business, Management and Accounting. The search keywords are equipment AND construction AND (selection OR choice). The resulting 451 items are reduced to 36 items by searching the keyword “decision support” within the results. Lastly, the items are reduced to 17 items by selecting only items that contain the exact keywords "Equipment" OR "Construction Equipment" OR "Equipment Selection". The screening of the abstracts is performed to exclude articles with no to low relevance to our field of study. This reduces the data to seven highly relevant items further analysed to extract requirements that must be considered when designing DSS in the field of construction equipment selection.

Table 1. Results of the literature analysis.

| Requirement                        | [12] | [13] | [14] | [15] | [16] | [17] | [18] |
|-----------------------------------|------|------|------|------|------|------|------|
| Define all relevant decision criteria | x    | x    | x    | x    | x    | x    | x    |
| Include expert knowledge          | x    | x    | x    | x    | x    | x    | x    |
| Weight the criteria               | x    | x    | x    | x    | x    | x    | x    |
| Consider project needs            | x    | x    | x    | x    | x    | x    | x    |
| Consider preferences              | x    | x    | x    | x    | x    | x    | x    |

Table 1 presents the results of the literature analysis by highlighting the major requirements that are summarised in the following. DSS are used for the selection of the optimal solution between a set of available alternatives. The major requirement is the identification of all the criteria or variables that are relevant for the selection problem [12–14,17,18]. Here, also the definition of the weights of the criteria that have impact on the selection is necessary [13,17,18]. In many selection problems it is essential to involve domain experts and use their knowledge for the development of DSS [13–15,18]. The
selection of the best alternative must be based on the conditions and needs of a specific project [13,16,18]. Another requirement is the integration of preferences [12] or the definition of preference functions [17] to assess alternatives.

3. AD-based design of DSS in building construction

3.1. Preliminaries on AD
AD is a systematic procedure for design and was developed by Suh in the 1970s. In AD costumer, functional, physical and process domain are used to address a specific problem. Each of the domains contains associated design elements namely the customer needs (CNs), the functional requirements (FRs) and design constraints (Cs), the design parameters (DPs) and finally the process variables (PVs). AD theory is based on two axioms [8]: 1) The Independence Axiom requires that functional independence between functional elements must be maintained, i.e. by avoiding unnecessary interactions between FRs and DPs; 2) The Information Axiom requires that the information content of the design must be minimized, i.e. by selecting the solution with the slightest information content.

3.2. Identification of costumer needs (CNs)
Based on the requirements collected in Section 2, five major customer needs are derived for design of DSS for construction equipment selection: CN1 – DSS shall give advice on the choice between a set of available alternatives; CN2 – DSS shall consider all the relevant criteria of the problem domain and weight them; CN3 – DSS shall exploit expert knowledge; CN4 – DSS shall consider available information and project-specific needs; CN5 – DSS should consider preferences of users in terms of utilities.

3.3. Top-level functional requirements (FRs) and design parameters (DPs)
Based on the identified CNs, the top-level FRs and DPs are defined. FR0 represents the main objective: “Provide support to make rational decisions in construction equipment selection”. To satisfy FR0 the design solution at the highest hierarchical level, DP0 is defined: “DSSs for construction equipment selection”. The top-level decomposition tree represented in Figure 1 links the top-level FRs to DPs. Design fields (DF) are defined to allow an efficient presentation of the results.

![Figure 1. Top-level decomposition tree (FR-DP).](image)

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 \\
X & X & 0 \\
X & X & X
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix}
\] (1)

The design matrix at the top level (1) has a decoupled design, showing the interdependencies between DPs and FRs, and establishes a defined order of implementation of the design solutions. In summary, the top-level pairs indicate the following requirements: 1) to exploit expert knowledge for defining alternatives and decision criteria, and to structure and store available knowledge; 2) to
compute the best rational decision between a set of available alternatives and give recommendations; 3) to use available project information, to insert preferences of the users and to get recommendations.

3.4. Decomposition and mapping of FRs and DPs

The top-level FR-DP pairs are further decomposed to transform the abstract requirements into more tangible design solutions that are relevant for the development and the implementation of DSS to be used for construction equipment selection. The results of the decomposition and mapping process are presented in Table 1, 2 and 3.

**Table 1. DF₁ Knowledge base**

| FRs                          | DPs                               |
|------------------------------|-----------------------------------|
| 1.1 Elicit the qualitative part of the model | 1.1 Decision network modelling tool |
| 1.1.1 Define the variables    | 1.1.1 Variable elicitation tool    |
| 1.1.2 Define the relations between the variables | 1.1.2 Causal relations definition tool |
| 1.2 Elicit the quantitative part of the model | 1.2 Decision network implementation tool |
| 1.2.1 Define the probabilities | 1.2.1 Conditional probabilities elicitation tool |
| 1.2.2 Define the utility function | 1.2.2 Utility function definition tool |
| 1.3 Store data                | 1.2.3 Database                     |

**Table 2. DF₂ Inference Engine**

| FRs                          | DPs                               |
|------------------------------|-----------------------------------|
| 2.1 Compute which decision yields the MEU | 2.2 MEU computation module |
| 2.2 Evaluate information and give recommendations | 2.1 Value of Information computation module |

**Table 3. DF₃ User Interface**

| FRs                          | DPs                               |
|------------------------------|-----------------------------------|
| 3.1 Visualise decision network | 3.1 Decision network visualisation tool |
| 3.2 Insert available project information | 3.2 Evidence entry field |
| 3.3 Insert user preferences   | 3.3 Preferences entry field       |
| 3.4 Answer to recommendations | 3.4 Question & answer tool        |
| 3.5 Get advice on the best rational decision | 3.5 Advice display |

3.5. Design guidelines and summary

Based on the mapping and decomposition process of the DFs we can now derive the guidelines for designing DSS in the construction phase (see Figure 2). The AD-based approach provides developers with an instrument sequencing the development of the single software modules and components. In our field of study, the problem domain concerns the selection of the construction process or task that could be enhanced by using advanced equipment.

The first main component of the DSS is represented by the knowledge base. Here, existing knowledge of the problem domain is used to i) define the qualitative part of the decision model, and ii) to implement the quantitative part of the decision model. Once the construction process or task for which the most adequate equipment must be selected is defined, the qualitative part of the decision model is implemented by identifying alternatives, variables, and causal relations between them. The alternatives are the available decisions, i.e., the equipment that can be employed for executing a
specific task or process. The variables represent the criteria that affect the decision between the different alternatives. To define alternatives, variables, and causal relations the analysis of literature, data, and the expert interviews should focus on exploring the following main groups of criteria: i) Technical criteria [12–14, 16–18]: specifications, characteristics, and performance of the equipment; ii) Economic criteria [12–14, 17, 18]: renting costs or lifecycle costs of the equipment; iii) Project specific criteria [13–16, 18]: available evidence like budget, time and site constraints of a specific project; iv) Safety and risk criteria [13, 14, 16]: health, safety and risk issues related to the operation of equipment; v) Environmental criteria [14, 15]: environmental impacts or damages caused by the equipment. Once the qualitative part of the decision model is defined, the model can be implemented by defining the numbers that are needed for performing the computations. The implementation of the numbers concerns the elicitation of conditional probabilities, that can be defined by mapping verbal statements of domain experts [10], or from data when available, and the definition of the utility function.

The second main component of the DSS is the inference engine, where computations are performed. The expected utility for every alternative is computed also based on weights defined by the user. According to the principle of MEU the system selects the alternative that yields the highest expected utility and provides this information to the user interface. Furthermore, value of information theory is exploited to determine which variables have the highest impact on the decision. This information is also sent to the user interface to give recommendations on which information should be provided or acquired to improve the decision.

The third main component of the DSS is the user interface. This component supports users in the selection of the most appropriate equipment for a specific construction project. Within the user interface the decision network on which the computations are based is visualised. The user has the possibility to insert the project specific information, any available evidence, or specific needs of the user or the construction site. In addition, the user can also state his subjective preferences, by weighting the parameters that are contained in the utility function. The user can enhance the results by following the recommendations of the inference engine by providing additional information on variables. Lastly, the user interface displays which alternative should be chosen.

| Definition of the problem domain: Construction process or task | DF, Knowledge base | DF, Inference Engine | DF, User interface |
|-------------------------------------------------------------|--------------------|----------------------|--------------------|
| Collect knowledge and data related to a construction process or task and structure it | Literature analysis, Expert interviews | Determine the best rational decision and give recommendations | Interact bidirectionally with the user who must evaluate alternatives for a specific project |
| Elicit the qualitative part of the model | Define variables | Decision network | User needs, evidence |
| - Alternatives (e.g. traditional excavation, equipment 1, 2) | Compute which decision yields the maximum expected utility | | |
| - Variables (technical, economic, project specific, safety and risk, environmental) | Compute expected utility of all the available alternatives using the weights defined by the user and select the action that yields the MEU | | |
| - Define relations between variables | Evaluate information and give recommendations | Insert available project information | Insert evidence about criteria (e.g. available budget, execution time, constraints) |
| Elicit the quantitative part of the model | Define probabilities | Insert user preferences | Insert weights of the parameters that impact utility (e.g. productivity, budget) |
| - Define conditional probabilities with domain experts or from data | Determine variables that affect utility, define utility function and utilities | Answer to recommendations | Acquire additional evidence to improve results (e.g. necessary lifting capacity) |
| - Define utility function | Store the elicited information in a database | Get advice | Decide that yields MEU (e.g. best rational decision is equipment 1) |

**Figure 2.** Design guidelines for implementing DSS for construction equipment selection.

**4. Conclusion**

This paper presents an AD-based approach for designing guidelines for the implementation of DSS for construction equipment selection. CNs are gathered from the characteristics of decision theoretic expert systems and an analysis of literature. Subsequently, FRs and DPs are derived by using AD decomposition and mapping. Finally, FRs and DPs are transformed into the design guidelines represented in Figure 2. The use of the guideline to implement DSS for construction equipment selection can aid the introduction of technological solutions in the construction industry.
References
[1] Rauch E, Vickery A, Garcia M, Rojas R and Matt D T 2018 Axiomatic Design based Design of a Software Prototype for Smart Shopfloor Management ed E C N Puik, J T Foley, D S Cochran and M L Betasolo MATEC Web Conf. 223 01012
[2] Pasetti Monizza G, Bendetti C and Matt D T 2018 Parametric and Generative Design techniques in mass-production environments as effective enablers of Industry 4.0 approaches in the Building Industry Autom Constr 92 270–85
[3] Marcher C, Giusti A, Schimanski C P and Matt D T 2019 Application of Decision Support Systems for Advanced Equipment Selection in Construction Cooperative Design, Visualization, and Engineering Lecture Notes in Computer Science vol 11792, ed Y Luo (Cham: Springer International Publishing) pp 229–35
[4] Power D J 2002 Decision support systems: concepts and resources for managers (Greenwood Publishing Group)
[5] Jato-Espino D, Castillo-Lopez E, Rodriguez-Hernandez J and Canteras-Jordana J C 2014 A review of application of multi-criteria decision making methods in construction Autom Constr 45 151–62
[6] Marcher C, Giusti A and Matt D T 2020 Decision Support in Building Construction: A Systematic Review of Methods and Application Areas Buildings 10 170
[7] Hodgett R E 2016 Comparison of multi-criteria decision-making methods for equipment selection Int J Adv Manuf Technol 85 1145–57
[8] Suh N P 1998 Axiomatic Design Theory for Systems Res Eng Des 10 189–209
[9] Russell S J, Norvig P and Davis E 2010 Artificial intelligence: a modern approach (Upper Saddle River: Prentice Hall)
[10] Kjærulff U B and Madsen A L 2013 Bayesian Networks and Influence Diagrams: A Guide to Construction and Analysis vol 22 (New York, NY: Springer New York)
[11] Horvitz E J, Breese J S and Henrion M 1988 Decision theory in expert systems and artificial intelligence International Journal of Approximate Reasoning 2 247–302
[12] Jankovic I, Djenadic S, Ignjatovic D, Jovancic P, Subaranovic T and Ristovic I 2019 Multi-criteria approach for selecting optimal dozer type in open-cast coal mining Energies 12
[13] Alshibani A, Elssir H, Al-Najjar M and Hamida H 2019 AHP based approach for crane selection of building construction in Saudi Arabia: A case study Proc Annu Conf Can Soc Civ Eng 2019 Canadian Society for Civil Engineering Annual Conference, CSCE 2019 vol 2019 June (Canadian Society for Civil Engineering)
[14] Waris M, Panigrahi S, Mengal A, Soomro M I, Mirjat N H, Ullah M, Azlan Z S and Khan A 2019 An Application of Analytic Hierarchy Process (AHP) for Sustainable Procurement of Construction Equipment: Multicriteria-Based Decision Framework for Malaysia Mathematical Problems in Engineering 2019 1–20
[15] Zeynalian M and Dehaghi I K 2018 Choice of optimum combination of construction machinery using modified advanced programmatic risk analysis and management model Sci. Iran. 25 1015–24
[16] Peng L and Chua D K H 2017 Decision Support for Mobile Crane Lifting Plan with Building Information Modelling (BIM) Procedia Eng. 7th International Conference on Engineering, Project, and Production Management, EPPM 2016 vol 182, ed Halicka K., Nazarko L., and Wasiak A. (Elsevier Ltd) pp 563–70
[17] Temiz I and Calis G 2017 Selection of Construction Equipment by using Multi-criteria Decision Making Methods Procedia Eng. Creative Construction Conference, CCC 2017 vol 196 (Elsevier Ltd) pp 286–93
[18] Marzouk M and Abubakr A 2016 Decision support for tower crane selection with building information models and genetic algorithms Autom Constr 61 1–15