Application of Systematic Design Methods to Cultural Heritage Preservation

To cite this article: Lorenzo Fiorineschi *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **949** 012029

IOP Conf. Series: Materials Science and Engineering **949** (2020) 012029 doi:10.1088/1757-899X/949/1/012029

Application of Systematic Design Methods to Cultural Heritage Preservation

Lorenzo Fiorineschi[1], Roberta Barsanti[2], Gaetano Cascini[3], Federico Rotini[1]

[1]Department of Industrial Engineering, University of Florence, Italy

[2]Museo Leonardiano of Vinci, Italy

[3]Dipartimento di Meccanica, Politecnico di Milano, Italy

lorenzo.fiorineschi@unifi.it; r.barsanti@comune.vinci.fi.it; gaetano.cascini@polimi.it; federico.rotini@unifi.it.

Abstract. The preservation of cultural heritage often involves the design of systems with different purposes, as for example the devices for extraction of data from inaccessible locations and/or demonstrative models. For the latter, when the starting information about the model to be designed is incomplete, the task is not trivial, and different interpretations of the system can lead to different design outcomes. Moreover, other requirements concerning size, materials and interactivity, make this a real engineering design task, where actors with conflicting needs can be involved. Accordingly, to ensure a comprehensive fulfilment of the task, it is possible to follow engineering systematic design approaches that, even if originally developed for the development of industrial systems, can be conveniently used for different fields of application. More specifically, these design methods ensure the design of cost-effective solutions by reducing the useless and costly design iterations that often characterize non-structured procedures. In particular, the present paper shows the application of systematic methods for the interpretation, the design and the development of realistic physical models from some of the Leonardo da Vinci's machines, for the Museo Leonardiano of Vinci (Italy). The followed approach allowed to efficiently gather the starting list of design requirements, and to engage a successful interaction among the designers, the historians, the museum staff and the architect involved in the showroom design. The key points of the systematic design methodology are presented in this paper, together with some applicative examples from the Da Vinci's models. Other possible application of systematic design approaches are also presented, with the aim of showing some representative examples were the Engineering design and problem-solving methods can support the preservation of cultural heritage.

1. Introduction

The preservation of cultural heritage (CH) often involves the design of systems with different purposes, as for example the devices for extraction of data from inaccessible locations [1] and/or the design of museum models and layouts [2]. Focusing the attention on demonstrative physical models, when the starting information about the system to be reproduced is incomplete, the design task is not trivial, and different interpretations can lead to different design outcomes. Moreover, requirements about the size, the involved materials and the expected interactivity, make this a real engineering design task, where different actors (e.g. architects, engineers, historians, technicians, etc.) with conflicting needs can be involved.

To ease the work of the designers, some methodological support can be found in literature (e.g. the Axiomatic Design [3], the Total Design [4], The Systematic Design [5]), as well as specific approaches to improve creativity in the design process [6], [7]. However, orienting through the variety of possible methods and tool is not trivial, and the selection of the most suitable item should be performed with care, in order to ensure its correct application. Moreover, it is possible to assert that the efficiency of the approaches can be ensured only if their application is guided by practitioners with high expertise.

The aim of this paper is to show that also for CH-related design task it is possible to follow systematic design and problem solving approaches that, even if originally developed for the development of industrial systems, can be conveniently used for different fields of application. More specifically, these design methods ensure the design of cost-effective solutions by reducing the useless and costly design iterations that often characterize non-structured procedures. In particular, the present paper shows the application of systematic methods for the interpretation, the design and the development of realistic physical models of some Leonardo Da Vinci's machines, for the Museo Leonardiano of Vinci (Italy). The followed approach allowed to efficiently gather the starting list of design requirements, and to engage a successful interaction among the designers, the historians, the museum staff and the architect involved in the showroom design. The key points of the systematic design and problem solving methodologies are presented in this paper, together with some applicative examples from the Da Vinci's models. Other possible application of systematic design approaches are also presented, with the aim of showing some representative examples were the engineering design and problem-solving methods can support the preservation of cultural heritage.

2. Systematic design and problem solving approaches

During the last decades, lot of research efforts have been spent on Design Theories and Methodologies, producing important contributions about both descriptive and prescriptive design models. While the former are devoted to investigate processes, strategies and methods used by designers, the latter provide instructions about how the design should be performed or which attributes the design artefacts should have [8]. Since prescriptive models recommend best practice guidelines, they are widely taught in engineering schools or reported to be applied in some industrial practice [9]. Accordingly, most diffused prescriptive models are based on the German systematic design approach from the 1970s [5], [10]. Additionally, the TRIZ [11] theory of problem solving is also acknowledged to efficiently support creativity in design and product development processes.

2.1. The Systematic Design approach

One of the most acknowledged systematic approach is that of Pahl and Beitz [5], which is based in the subdivision of the design process into four (iterative) main phases :

- Task clarification: where the design task is formulated according to the set of requirements.
- Conceptual design: where the fundamentals of the design outcomes are outlined.
- Embodiment design: where the issues about size, materials and kinematics are investigated and optimized. In this phase, it is possible to exploit lot of Computer Aided Engineering (CAE) tools.
- Detail design: where the final embodiment is completed in each detail, up to the drafting of the production documents.

The first two phases are acknowledged to be the most impacting ones, and especially concerning the conceptual design phase, the systematic design provides one of the most largely diffused method, i.e. the Functional Decomposition and Morphology (FDM). Accordingly, among the positive characteristics acknowledged for FDM, it is possible to highlight the ease of being learned and self-applied after a short period of practice [12]. In a few words, FDM requires that the overall function of the system to be designed is decomposed into simpler sub-functions. Subsequently, working principles (WP) are identified for each single sub-function and, eventually, WP are systematically combined each other to obtain one or more overall concept variants.

Recently, still with the aim of overcoming some of the FDM flaws and providing a systematic model to support the conceptual design phase, the Problem-Solution Network (PSN) approach has been proposed [13]. In particular, this approach is based on the co-evolution of design problems and related solutions, which can be used in a structure way in order to comprehensively explore the design space [14].

2.2. Introduction to TRIZ

TRIZ is the Russian acronym for "Teoriya Resheniya Izobretatelskikh Zadach", i.e. the "theory of the resolution of inventive problems" that was formerly developed by Genrich Altshuller [15]. The three main observations made by Altshuller as a consequence of his noticeable research effort, can be summarized as it follows [16]:

- Technical systems evolve according to objective laws, toward an increasing degree of ideality (i.e. the ratio between benefits and the sum of costs and harmful effects).
- Any specific technical problem can be converted into a more general one through an abstraction process. Thanks to the abstraction, Altshuller observed that similar problems arise in very different fields, allowing to group the related solving processes in a finite number of "solving principles".
- Given a finite number of standardized problems and solving principles, solutions based on similar concepts can be used for solving apparently different technical problems. Consequently, it has been possible to build the invention theory, aimed at finding the most effective conceptual path for the generation of a solution.

According to the above-mentioned considerations, many inventive tools have been developed (part of them shortly introduced in Appendix), now constituting the TRIZ toolset. TRIZ actually supports problem solving and innovative solutions development, troubleshooting and failure prevention, incident management, new products-services-business concepts definition and administrative/management conflict resolution. Therefore, it looks like a toolbox containing a set of tools to be conveniently selected, according to the specific needs. However, it is worth to notice that the selection of the tools is currently guided only by the experience of the user; therefore, he/she should be well trained for ensuring a correct application.

Many attempts have been made in order to merge the potentialities of the German systematic approach with that of TRIZ [17], [18], in order to exploit the benefits of a procedural approach with those of inventive tools [19].

3. Examples of possible applications

3.1. The TRIZ-based classification of the cranes designed by Filippo Brunelleschi

During the 15th century, some of the most acknowledged buildings of Florence were built and/or were under construction (e.g. Palazzo Pitti, S. Lorenzo Basilica, S. Spirito Basilica, Ospedale degli Innocenti, S. Maria degli Angeli, etc.), among which the Santa Maria del Fiore cathedral. Filippo Brunelleschi (Florence 1377 – Florence 1446) was asked to build the dome lantern of the cathedral, which is a construction with a not negligible size.

The "Opera del Duomo" archive stores a very detailed report on the expenses for the erection and the maintenance of S. Maria del Fiore cathedral. However, this data are not sufficient for historical analyses, because Brunelleschi used to destroy all information about his machines. Fortunately, among all the drafts representing the Brunelleschi cranes, those made by Leonardo represent the most comprehensive collection and are clearer and richer of constructive details than any other.

By starting from the information collected by Leonardo da Vinci, and exploiting all other available documents, TRIZ was successfully exploited to aid historians classification of the cranes designed by Filippo Brunelleschi to build the Dome of the S. Maria del Fiore Cathedral [20], [21]. TRIZ has been also used in a similar application focused on Leonardo da Vinci's textile machines [22].

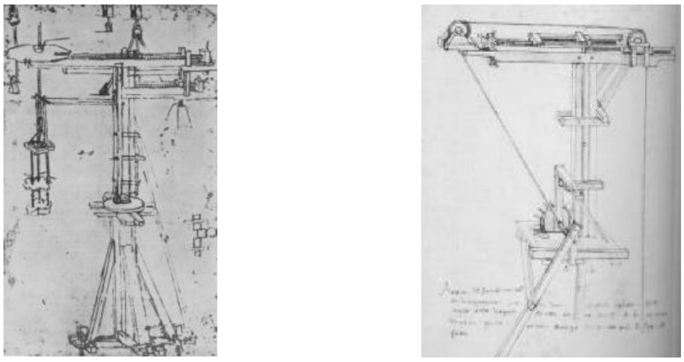


Figure 1. Two of the available crane drawings used for the classification [20] (On the left: Leonardo da Vinci Cod. Atl. f.965r. On the right: Bonaccorso Ghiberti B.R.228 f.107 v)

3.2. Embodiment design of the Leonardo's axial bearings

Among the plethora of futuristic devices designed by Leonardo da Vinci, there are the axial bearing concepts represented in Figure 2. However, only partial conceptual information were retrievable from the Leonardo's documents. Moreover, the same Leonardo was sceptic about the functioning of some of them (the last two in the Cod. Madrid 101 v).

Therefore, in order to gather information about the actual functioning of the bearing concepts, it was necessary to apply the systematic design process depicted in Section 2. More precisely, by assuming the Leonardo's documents as the outcome of the conceptual design phase, it was possible to proceed with the embodiment design phase, by exploiting modern CAE tools in order to build virtual prototypes (Figure 2).

In particular, thanks to the CAD models it was possible to perform virtual simulations that allowed to identify the criticalities of the Leonardo's sketches.

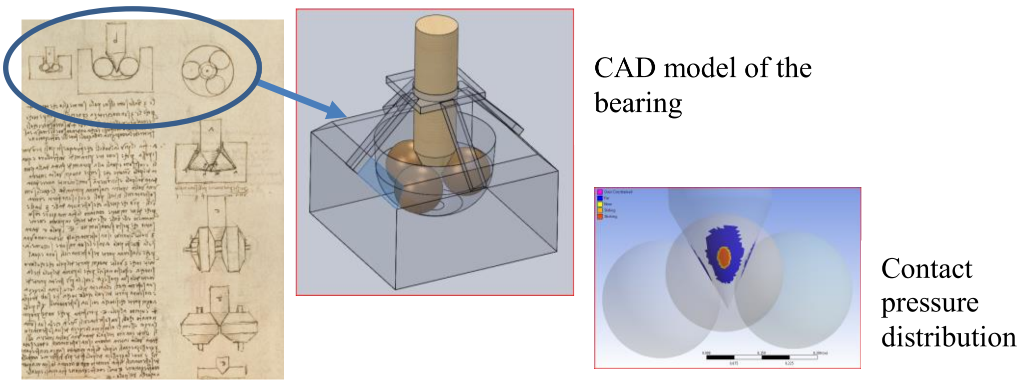


Figure 2. Leonardo's bearing concepts from the Madrid code 101v, and the virtual models realized to understand the feasibility of the physical models.

As a result, the most promising concepts have been identified in terms of kinematic functioning, and structural evaluations have also been performed about the contact pressure between the rolling elements. In particular, by following the systematic procedure depicted in Section 2, i.e. by splitting the research

IOP Conf. Series: Materials Science and Engineering **949** (2020) 012029 doi:10.1088/1757-899X/949/1/012029

work into the conceptual and the embodiment design phases, it was possible to easily manage the process and the different skills of the persons involved in the work. Indeed, while historians and engineers were focused on the interpretation of the Leonardo's documents (i.e. the conceptual design phase) from both the aspects, the analysis of the historical context and the identification of the working principle, engineers built the virtual models in order to perform realistic simulations for the verification of the functioning. Therefore, an agile and easy-to-manage iterative process was followed between these two phases, in order to obtain the final information.

This kind of information was fundamental in order to allow the team architect to build realistic virtual animations (considered here as the outcome of the "detail design phase"), which can be currently viewed at the "Museo Leonardiano" museum in Vinci (Florence, Italy).

3.3. Design of physical models for the "Museo Leonardiano" of Vinci

The engineering design approach can of course be applied for the realization of physical models for museums. In this case, the process is complete, because starts from the elicitation of the set of requirements and proceeds across all the phases depicted in Section 2, thus allowing to perform the manufacturing operations. Figure 3 shows some of the models designed for the Museo Leonardiano of Vinci.

Figure 3. Physical models designed for the Museo Leonardiano of Vinci

In the next section, an illustrative example is reported to show the most important key point of the design process, which led to the manufacturing of the models.

4. Illustrative example: the Leornardo's hydraulic saw.

4.1. Task clarification

The museum staff asked to redesign a new and fully functional model of the hydraulic saw of Leonardo (Cod. Atl. F 1078r), with realistic materials and appearance. Therefore, according to the checklist of Pahl et al. [5], the requirement elicitation process started. In particular, requirements about geometry (especially the size), kinematics, materials, forces (e.g. due to the possible human interactions), production process and costs were considered. This process involved the engineering designers, the museum staff and the manufacturer, but the systematic procedure allowed to easily manage the multidisciplinary exchange of information.

4.2. Iterations between the conceptual and the embodiment design phase

The concept described by the sketches of Leonardo needed to be better investigated by means of different embodiment models. In particular, some preliminary hypothesis have been formulated about the underpinning mechanisms, also referring to existing models from other museums.

After few iterations between the conceptual design phase (where the hypothesis about the working principles were formulated) and the embodiment phase (where the virtual models were tested), it was possible to definitely extract the information about the kinematic of the system.
Figure 4 reports the identified key details, which are used in the following paragraph to shortly describe the functioning of the system. The last version of the CAD model used to perform the multibody simulations required for the identification of the kinematic, is shown in Figure 5.

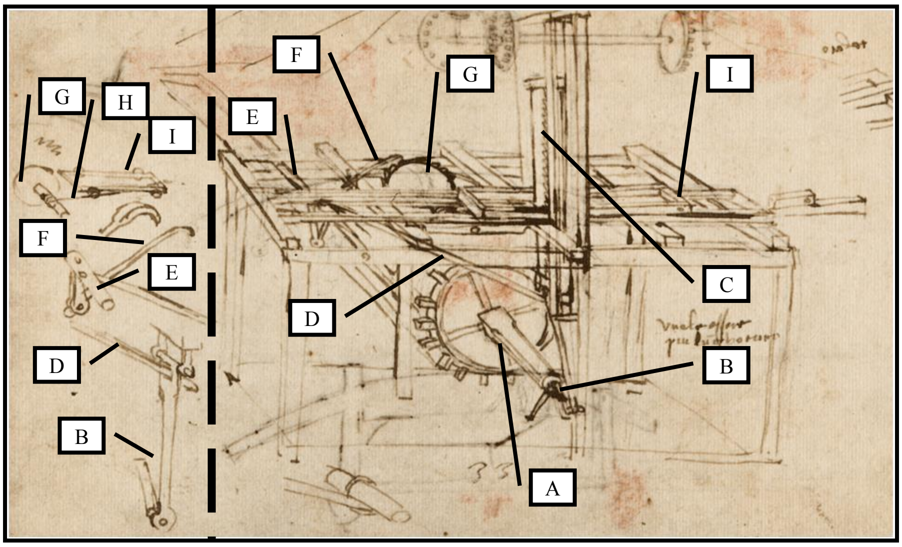


Figure 4. Details of the Leonardo's hydraulic saw (Cod. Atl. F 1078r).

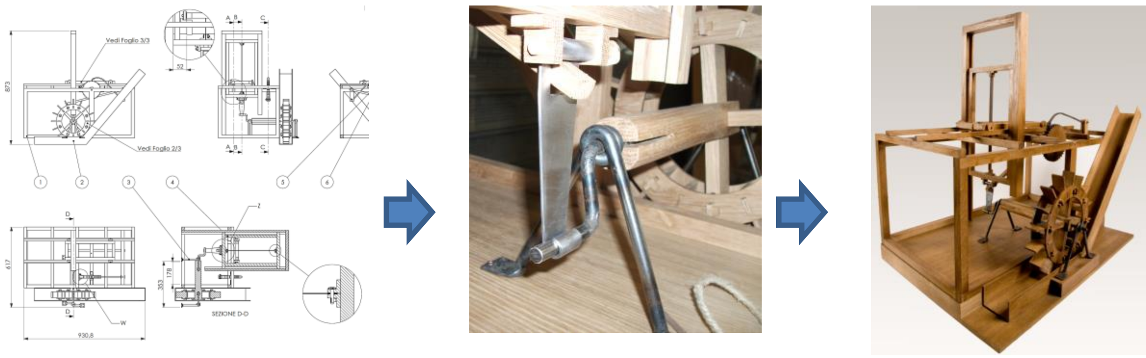
The motion starts from the wheel "A" and transmitted to the crank-shaft mechanism "B", which moves the blade "C", and the oscillating bar "D" and the shaft "E". The shaft "E" is linked to the grappling hook "F" which engages with the wheel "G" thanks to the effect of gravity. Therefore, the hook "F" impresses a rotation of the wheel "G" and the related shaft, where a rope "H" is rolled up. The same rope "H" is connected to the carriage "I", which will proceed forward of a step (from the right to the left in Figure 4), for each lap of the wheel "A" and for each movement of the blade "C".

Figure 5. CAD model of the final embodiment of the saw

Thanks to this information, it was possible to interact with the final model manufacturer in order to start the realization of the final embodiment of the system.

4.3. Detail design and model construction
The CAD model built in the embodiment design phase constitutes the starting point for the detail design phase. The manufacturer was of course involved also in the precedent design phases, but in this one the designer needs to work in strict contact with him, in order to find the best solutions in terms of

manufacturing processes, details (e.g. how to hide screws, or how to obtain the desired surface appearance, etc.) and costs.
Therefore, as shown in Figure 6, final production documents have been realized and sent to the manufacturer, who used them as reference during the manufacturing operations that led to the final museum model.



Technical drawings Manufacturing process Final museum model

Figure 6. From the technical drawings to the final physical model, currently viewable at the Museo Leonardiano of Vinci (Italy).

5. Conclusions

The aim of the paper was to provide a short and non-representative overview of the possible support that the systematic design methodologies can provide in cultural heritage tasks. As shown in Section 3, the field of application is not limited to design tasks, but the available tools and procedures can be conveniently used for a plethora of other applications, like the classification and/or the analysis of the technological evolution path.

Obviously, the applicability of the approaches is also ensured for the design of any physical device involved in cultural heritage operations. In this case, the major impact of the available methods and tools is given in terms of "creativity", allowing the designers to rapidly identify cost-effective solution with the highest possible efficiency.
Therefore, the approaches and tools shortly introduced in this paper through the mentioned application examples, show that engineering design methods can be efficiently used for cultural heritage purposes, allowing to reach optimal results.

Acknowledgements
This models shown in this paper have been designed and realized with the funding provided by the Museo Leonardiano Piazza dei Guidi - 50059 Vinci (Florence) - Italy. http://www.museoleonardiano.it

References

[1] B. Allotta *et al.*, "MARTA: an AUV for underwater cultural heritage," *Proceedings of the Underwater Acoustics 2014*, no. June, 2014.
[2] A. Chianese and F. Piccialli, "Designing a smart museum: When cultural heritage joins IoT," in *Proceedings - 2014 8th International Conference on Next Generation Mobile Applications, Services and Technologies, NGMAST 2014*, 2014, pp. 300–306.
[3] N. P. Suh, "Axiomatic Design Theory for Systems," *Research in Engineering Design*, vol. 10, pp. 189–209, 1998.

[4] S. Pugh, *Total Design. Integrated Methods for Succesfull Product Engineering*. Reading, Massachusetts: Addison Wesley Publishing Company, 1991.
[5] G. Pahl, W. Beitz, J. Feldhusen, and K. H. Grote, *Engineering design 3rd ed*. Springer-Verlag London, 2007.
[6] J. J. Shah, N. Vargas-Hernandez, J. D. Summers, and S. Kulkarni, “Collaborative Sketching (C-Sketch) - An Idea Generation Technique for Engineering Design,” *The Journal of Creative Behavior*, vol. 35, no. 3, pp. 168–198, Sep. 2001.
[7] J. S. Linsey, E. F. Clauss, T. Kurtoglu, J. T. Murphy, K. L. Wood, and a. B. Markman, “An Experimental Study of Group Idea Generation Techniques: Understanding the Roles of Idea Representation and Viewing Methods,” *Journal of Mechanical Design*, vol. 133, no. 3, p. 031008, 2011.
[8] S. Finger and J. R. Dixon, “A Review of Research in Mechanical Engineering Design. Part II: Representations, Analysis, and Design for the Life Cycle,” *Research in Engineering Design*, pp. 121–137, 1989.
[9] T. Tomiyama, P. Gu, Y. Jin, D. Lutters, C. Kind, and F. Kimura, “Design methodologies: Industrial and educational applications,” *CIRP Annals*, vol. 58, no. 2, pp. 543–565, Jan. 2009.
[10] W. Eder and S. Hosnedl, *Design Engineering - A Manual for Enhanced Creativity -*. CRC Press, 2008.
[11] G. S. Altshuller, *Creativity as an exact science.* Amsterdam: Gordon and Breach Science, 1984.
[12] J. Jänsch and M. P. Weiss, “Evaluation and Similarity of Systematic Methods for the Conceptual Design of New Products,” in *Proceedings of the 9th Biennial ASME Conference on Engineering Systems Design and Analysis*, 2008, no. JANUARY 2008, pp. 209–222.
[13] L. Fiorineschi, F. Rotini, and P. Rissone, “A new conceptual design approach for overcoming the flaws of functional decomposition and morphology,” *Journal of Engineering Design*, vol. 27, no. 7, pp. 438–468, 2016.
[14] L. Fiorineschi, “Abstraction framework to support students in learning creative conceptual design,” *Journal of Engineering, Design and Technology*, vol. 16, no. 4, pp. 616–636, 2018.
[15] J. Terninko, A. Zusman, and B. Zlotin, *Systematic Innovation: An introduction to TRIZ (Theory of Inventive Problem Solving)*. CRC Press, 1998.
[16] G. Cascini, “TRIZ-based anticipatory design of future products and processes”,” *Journal of Integrated Design & Process Science*, vol. 16, no. 3, pp. 29–63, 2012.
[17] L. Fiorineschi, F. S. Frillici, and F. Rotini, “Enhancing functional decomposition and morphology with TRIZ: Literature review,” *Computers in Industry*, vol. 94, no. January, pp. 1–15, Jan. 2018.
[18] F. S. Frillici, L. Fiorineschi, and G. Cascini, “Linking TRIZ to conceptual design engineering approaches,” in *Procedia Engineering*, 2015, vol. 131.
[19] L. Fiorineschi, F. S. Frillici, F. Rotini, and M. Tomassini, “Exploiting TRIZ Tools for enhancing systematic conceptual design activities,” *Journal of Engineering Design*, vol. 29, no. 6, pp. 259–290, 2018.
[20] G. Cascini, R. Nanni, and D. Russo, “TRIZ Patterns of Evolution as a means for supporting History of Technology : analyzing the Brunelleschi ’ s Dome cranes,” *TRIZ Journal*, no. July, 2003.
[21] D. Russo, “I modelli di evoluzione tecnologica TRIZ come strumento di supporto per la Storia della Scienza e della Tecnica – Il Cantiere di S. Maria del Fiore,” Università degli Studi di Firenze, 2003.
[22] G. Cascini, D. Russo, and R. Nanni, *A Contribution to History of Technology: Analyzing Leonardo’s Textile Machines and His Inventive Process by TRIZ Methods*. Florence, 2004.