Architecture of a hybrid manufacturing plant: conceptual design issues

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Abstract. The purpose of the presented paper is to identify and examine the key innovation areas in architectural design for manufacturing plants that are likely to appear due to the recent progress in the production technology. Firstly, the principles of the hybrid manufacturing system are discussed, with regard to the effects that the recent shift of production paradigm brings organisation to the work as well as to the character of human participation in the industry. In the next step, the analysis of exemplary designs is used to investigate new tasks and difficulties that this change is likely to pose to the architects. The research method is a logical analysis, while the material used consists of empirical designs realised with architecture master students. The most significant design issues encountered at different decision-making moments of the design process are subsequently discussed. They point to the stages of setting the functional programme, deciding upon the site selection, elaborating the factory plans and the composition of architectural form, as representing four key areas of design sequence for innovative concepts to emerge. Among other conclusions drawn from the study, the evidence for the growing importance of the aesthetics in design can be distinguished. This corresponds to the observed shift of design trends from the office to industry functions.

1. Introduction
As a result of the recent paradigm shift in production, hybrid manufacturing has multiple definitions developed simultaneously by different specialists, while the discussion on this topic constantly evolves towards new directions. Despite the wide range of definitions, the most fundamental feature of hybrid manufacturing is the coincidence of parallel production processes. The purpose of developing the concept of hybrid manufacturing, understood as the combination of two or more manufacturing processes, [1] is to boost the advantages of smart production, mainly orientated towards achieving the best efficiency with an optimised use of energy and resources. An important aspect of involving two or several processes in one hybrid production chain is the fact that these processes, parallel or sequential, can take place in separated environments. [2, p. 211] Initially, the goal of separating the processes was to enhance the product’s quality as well as the efficiency of the entire production process. [2] More recently, however, the aim of hybrid manufacturing “has also expanded to enabling the manufacturing of products that cannot be manufactured or fabricated by traditional manufacturing processes.” [2, p. 211] In order to function efficiently, the hybrid manufacturing model requires the development of cloud based services. Being a support for advanced manufacturing activities, cloud computing provides the enabling technologies for intelligent information processing [3, p. 1970] and comprises such services as a server, storage and databases, which are referred to as “cloud” services for the reason of being delivered from a remote location through a system controlled by a third party than the recipient. [4, p. 408] Enabling fast and efficient flow of information between diverse agents involved in the production process, cloud computing constitutes an essential element of the futuristic
Vision of a virtual factory, where work can be delivered by the involved entities from distinct locations. [2, p. 215]

At present, the literature on hybrid manufacturing consists of about 7000 research papers, mostly concentrated on the technology and computing related issues, with the development of cyber-physical systems and the Internet of Things being most commented. The cyber-physical system (CPS) consists in integrating physical devices (robots, machines) with data-processing elements (computers) and it constitutes one of the fundamental features of smart manufacturing systems. [5, p. 10] When it comes to the Internet of Things (IoT), this concept refers to machine-to-machine communication and interaction which occur without human assistance. As a network, the Internet of Things combines physical elements which are equipped with sensors, software and connectivity, in order to ensure an uninterrupted information flow between diverse entities involved in the manufacturing process [6, p. 1141]. Among other frequently discussed topics related to the hybrid manufacturing the themes of cyber-security and big data processing can also be distinguished.

On the contrary, the role of humans in hybrid manufacturing systems remains so far marginalised to the discussions on the human-robot relationship. [e.g. 7] From the point of view of an architect, the role of humans is essential as it has a bearing on the design methodology and principles adopted. Therefore, the purpose of the following work is to discuss what new tasks can potentially arise from the recent shift in manufacturing for the architects. In terms of the human work environment, which is more sensitive to design for than machine park area, the main questions raised are what roles are fulfilled by humans in hybrid manufacturing systems and what the relevant workplaces are. This information provides the basis for understanding key design issues related to developing a conceptual project for a hybrid factory. The subsequent question is how can architects prepare for new tasks and requirements that arise from the shift in production paradigm? The latter question is particularly important from the point of view of the education of future architects, which is why the research presented below assumes the participation of architecture students.

2. Methodology and materials
The research presented in this paper consists of two implementation stages. The first is based on literature analysis and seeks to define the essential typology of workplaces in a hybrid manufacturing plant. The second part of the research is grounded on an empirical study and covers a step-by-step analysis of the design process, implemented in parallel with the supervision of student projects realised within the Architectural Design of Workplaces design studio. The project theme was to develop a conceptual design for a modern manufacturing plant and, depending on the students' individual choice, some of the selected production profiles fall into the category of hybrid manufacturing. The process of their development was followed within the timeframe of weekly consultations, which served as a real time laboratory for examining difficulties in design practice that result from the recent shift of production paradigm. The logical analysis of projects’ development is aimed at identifying the essential cause and effect relations in the design praxis.

The materials elaborated with students in the framework of the same design studio were previously used to realise the research on the developing architectural trends regarding the design for creative industries, with a special focus on the facade composition and finishing materials used. [8] Moreover, their influence on the quality of public spaces has been explored. [9] More recently, the quoted design studio has provided materials to investigate the potential appearance of creative workplaces in Industry 4.0 as well as the typology of dining areas in modern factories. (unpublished) The presented paper will supplement the existing discussion with a view on the essential difficulties in architectural design practice that arise from the recent technological and social transformations in the industry.

3. Results and discussion
From a number of 138 projects collected so far in the archive of the concerned design studio, 59 projects of diverse industry branches (Graph 1) can be defined as modern manufacturing plants of small or medium scale, which are eligible for a further selection of proper examples.
Graph 1. The collected projects breakout by industry branch.

Considering the use of combined processes occurring in separate locations, together with data processing also from a remote location, as the main criteria of hybrid production, the ten most suitable projects were selected for further analysis. They represent fewer branches of industry, namely lamps (3), electronics (3), furniture & chairs (2), bicycles (1) and toys (1) production sectors. The development of these exemplary works has been analysed with an objective to identify and discuss the design difficulties arising from the shift from traditional manufacturing to hybrid.

In order to facilitate reading and comprehension, the results of the research will be discussed in subsections corresponding to the subsequent stages of the design process and the relevant decision-making moments.

3.1 The challenge of the visionary thinking. Setting the programme
The first step of the design consists of selecting an industry branch and setting the functional program to be realised. Already at this initial stage of the project, the architect encounters a major problem that is related to the visionary thinking about the object’s function. The reason is that hybrid production technologies are a novelty and therefore do not have manuals, while the existing factory design instructions and source books are considerably outdated. For this reason, the preliminary functional search is regularly based on study cases of existing enterprises with an identical or similar production profile. The designs literally based on study cases cannot be authentically innovative, for this reason, most of the projects collected in the archive of the concerned design studio have been excluded from the further study on the subject. Only in some cases would the projects’ authors search for a means of responding to the shifting production reality, reaching out for their own visionary ideas regarding the way of solving the functional layout as well as designing the work environment. The usual path in this regard begins with the analysis of existing programmes, which are subsequently modified by in order to match the shifting paradigm. Key modifications consist of minimising the spaces provided for the activities subject to reduction and, on the other hand, in providing additional space for developing and emerging functions. Besides the workplace areas, these include also recreational spaces for employees.
3.2 An updated point of view on site selection
Based on the analysis of selected architecture projects, it can be observed that the idea of hybrid manufacturing has a large impact on the preliminary stage of design which consists of function and site selection. Instead of typical outsourcing, hybrid manufacturing would rather assume parallel production in separate plants, with all processes being controlled simultaneously, possibly from a remote location. This gives an impulse to use the sites in the proximity of a major city that offers enough information and communication specialists, and frequently contains a technical university, as well as provides sufficient infrastructure. Subsequently, for the sake of reducing the transportation, the choice of location in the proximity of existing manufacturing plants is preferred, which is also intended to contribute to forming a cloud of cooperating factories.

3.3 Knowing the building’s users. Workplaces and facilities for employees
Another challenge that occupies the architect’s attention in the initial phase of the work on the project of a hybrid manufacturing plant is providing the right typology of spaces to serve the employees. While the literature on hybrid manufacturing reduces the discussion to the human-robot relationship, important information concerning the trends that will shape both human work environment as well as social areas in the factories of the future is to be found in the resources on Industry 4.0 vision, to which hybrid manufacturing conceptually belongs. Otherwise known as the industry of the fourth generation, the vision of Industry 4.0 has a significant impact on the role of humans in the production sector. Although the humans remain at the central position also in the industry of the future, the form of their participation shifts from the roles of industrial designers, draftsmen and operators of automated machines towards their new capacities as innovators and contributors. [10, p. 8] As further discussed by Daniel Buhr, the shift into smart manufacturing has some controversial aspects with regard to its effects on the labour market. First of all, there is a risk that the increasing automation and digitisation will have a reducing effect on the jobs offer in manufacturing. Among three potential organisation systems discussed by Daniel Buhr with regard to their application in smart manufacturing, the hybrid scenario is described as the one that combines both humans and objects in a network, which uses interactive and cooperative technologies to monitor and control the manufacturing process. [10, p. 8] In hybrid systems, the requirements for employees are generally greater, as they need to adjust and assume different roles in the manufacturing process, depending on the current situation. The recent shift of production paradigm proves to have a significant impact on what is considered as the employees’ key-competences, which are now interdisciplinary thinking, high IT competences, life-long learning ability and more active participation in problem solving and optimisation tasks. [11, slide 7] It can be concluded that hybrid organisation systems tend to combine creativity, which is so far only a human feature, along with a variety of technical skills that are regularly required from employees in industrial sectors. The changes in employee competencies do also translate into a hierarchical structure of staff. Namely, high flexibility of staff, who tend to work...
collectively in a loosely formulated network, is defined as the swarm work organisation [12, p. 4], in which the labour structure is not hierarchical, while the employees are equally active and qualified.

The unique combination of skills required from employees in hybrid systems, as well as their less hierarchical structure, are expressed in the typology of workplaces provided in the analysed exemplary projects. Among the key design features influenced by the new structure and competencies of staff, a less definite division into what is considered a regular workplace or a creative one can be considered. Because employees perform varied tasks, some of which are related to controlling and monitoring of the processes, while some other require active and creative problem solving, their work environment has to fit both kinds of activities. An interesting example of a workplace that combines diverse technical skills with creative imagination is prototyping and product’s improvement. The multi-faceted nature of such works is expressed in the flexibility of spaces as well as in the multifunctional character of the work environment. An exemplary solution that can potentially be used to achieve the effect of adjustable spaces are the movable partitions. (Figure 1) Their use in factory interiors is just one of multiple manifestations of the progressing transfer of architectural standards from contemporary office design to industrial plants. (Figures 2 & 3) An equivalent process of transferring architectural and aesthetic standards from the office to the industry can be observed in the design of social areas for employees, including locker rooms, rest areas and canteens. In particular, recreation areas show great similarity to office design standards, especially in terms of aesthetics.

![Figure 2. Interior design at the entry for both clients and employees. 3-D printers factory [14](image)](image)
3.4 Marketing approach
The idea to take advantage of highly advanced production technology in order to build the company's image corresponds to the marketing approach to design, quite often sponsored by the investor. The trend finds its reflection in the facade composition that is more refined than usual, as well as in the use of finishing materials of above average quality, as compared to the existing architectural models of manufacturing plants. (Figures 2 & 3)

In a limited number of cases, the idea of hybrid manufacturing finds its expression in the architectural form that is given to the factory building. For example, the idea of independent production lines, which nonetheless run in parallel, can be translated into a spatial layout combining three joint factories in one plan, connected by the facilities and managing units.

Another interesting effect of treating architecture as a tool for building a recognisable company image on the market can be observed in the size of surfaces designated for offices, showrooms and other types of promotional areas. The exemplary projects selected for the study prove that both spaciousness, as well as the aesthetics of interior design, might be related to the marketing goals of promoting the industrial plant in question.

| Design stage  | Design issue                      | Proposed solution                                                                 |
|---------------|-----------------------------------|-----------------------------------------------------------------------------------|
| 1. Programming| Lack of valid functional schemes  | Use existing models and verify its validity by:                                   |
|               |                                   | - downsizing functions subject to reduction                                        |
|               |                                   | - providing more space for developing functions and ideas                          |
|               |                                   | - providing clear division between spaces for humans and spaces for machinery      |

Table 1. Influence of hybrid manufacturing idea on architecture design at its key stages
2. Site selection  
Availability of resources, labour and transport  
Building up a group of related factories for more sustainability

3. Plan drafting  
Providing appropriate spaces for users  
New standards for the interior design of facilities for staff, e.g. recreation areas, canteens  
Emphasis on the aesthetics

4. Architectural form / facades concept  
Marketing  
Visible translocation of office design standards to industrial plants  
Emphasis on the aesthetics  
More space provided for showrooms and offices

**Figure 4.** Architect’s competencies at discussed stages of the conceptual design process

4. Conclusions
The results of the research allow identifying the key design stages in which the idea of the hybrid manufacturing challenges the architects and, at the same time, stimulates them as designers to conceive new solutions. Such situations were observed at the different stages of work. During the phase of preliminary studies, they were basically related to the decision-making moments while setting the investment’s functional programme as well as performing site analysis in the context of the selected function. The following important stages included plan elaboration, with particular regard to the issues of dividing the zones for humans and for machines, as well as of providing suitable spaces for employees, including proper recreation areas. Moreover, there is a legible emphasis on the aesthetics of interior design, which is seen as the means to inspire humans. The potential
solutions proposed to the major issues encountered at the mentioned stages of architectural design indicate the main direction for innovations in the factory design, while the revision of currently used standards proves to be necessary due to the recent paradigm shift in manufacturing sectors. (Table 1)

Finally, from the point of view of architects’ education, the key conclusions that can be drawn from the study are that the ability to respond individually to a design challenge will gain in importance, while the use of manuals and standard solutions will not work for new types of manufacturing plants. Among the emerging key competencies of the architect, the ability to cope with new situations, the capacity of visionary thinking as well as the creativity, which is crucial to design unique work environments, can be distinguished. (Figure 4) Training architecture students in these skills should be one of their education priorities. As it can be further ascertained, the abilities to analyse problems and synthesise assumptions remain crucial at different stages of the design, while the ability to reproduce a model solution in customised dimensions loses its significance. In order to train young architects in skills that will become required in relation with the emerging design tasks, more attention should be paid to conceptual work stages that particularly support the development of visionary thinking and creativity, in addition to the regularly used analytic tools.

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