Model for Devising Visual Management Systems on Construction Sites

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Abstract: Visual management (VM) is a strategy for information management that is widely used in the manufacturing industry, which is strongly related to increasing process transparency, one of the core principles of the lean production philosophy. However, the use of VM on construction sites is still relatively limited, and there is scant literature on the implementation of this principle in construction projects. This article proposes a model for devising visual management systems, understood as sets of visual practices that should be integrated in managerial processes. It is based on a set of benchmarking studies and two empirical studies carried out at different construction firms. As secondary contributions, this investigation proposes a set of guidelines for designing and implementing visual management systems and a taxonomy of VM practices according to the degree of integration in managerial processes. Some concepts proposed in other fields of knowledge, such as visual thinking, visual literacy, collaboration rituals, and boundary objects, were considered in the development of the model.
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Introduction

Process transparency is one of the core principles of the lean production philosophy. This principle has been defined as the ability of a production process (or its parts) to communicate with people (Formoso et al. 2002). This is achieved by ensuring that the main process flows are visible and comprehensible from start to finish, through organizational and physical means, measurements, and public display of information (Koskela 2000). It has been argued that if process transparency is successfully implemented, most problems, abnormalities, and types of waste that exist can be easily recognized in order to allow remedial measures to be taken (Igarashi 1991).

The concept of process transparency has evolved in the last few decades, and it is not only limited to lean manufacturing plants. In fact, it has been applied to a wide range of activities, including healthcare, financial markets, and green buildings (Khwaja and Schmeits 2014; Klotz et al. 2008; Graafland and Nijhof 2007). Despite the differences between applications of process transparency, a common benefit can be found in most of them: transparency enables increased participation and gives decision-making authority and ability to different stakeholders (Greif 1991; Klotz et al. 2008).

Tezel et al. (2016) defined visual management (VM) as a sensory strategy for information management, which is used to increase process transparency. It includes messages communicated through any of the five senses—taste, touch, smell, hearing, and sight (Galsworth 1997). One distinctive aspect of VM is that it is intended for a group and not just for an individual. Whereas in a conventional workplace most messages are transmitted by specific information channels, such as meetings and memos, in visual factories an information field is created, extending access to information to a large number of people (Greif 1991).

Other functions of VM have been pointed out in the literature; besides increasing process transparency, these include creating a sense of shared ownership and supporting on-the-job training (Tezel et al. 2016), facilitating collaboration among team members (Ewenstein and Whyte 2007), mitigating problems related to the management of complex production systems (Viana et al. 2014), and increasing workforce motivation (Galsworth 1997).

Some VM practices are well described in the literature, such as 5S (a systematic housekeeping method) (Gapp et al. 2008; Spagnol and Li 2015; Galsworth 1997), A3 reports (Sobek and Smalley 2011; Liker 2004), *kanban* (Thürer et al. 2016; Junior and Godinho Filho 2010; Costa and de Burgos 2015), standard operating sheets (Lyons et al. 2013), and *andon* (Kattman et al. 2012; Bamber and Dale 2000). However, the application of VM on construction sites is still relatively limited: (1) visual devices are mostly used in site offices to support managerial decisions, and at some construction sites only health and safety warning boards are found in working areas (Tezel and Aziz 2017b); and (2) most VM implementations in construction tend to focus on the use of individual tools to support specific operations, without considering the need to support production management as a whole (Kirchbach et al. 2014; Brady et al. 2013; Costa and de Burgos 2015).

Moreover, research on the process of devising and implementing VM systems is relatively scarce in construction management (Tezel et al. 2015). Recent research has mostly focused on the definition of categories for existing VM practices (Tezel et al. 2016) or on the impacts of visual devices or subsystems (Tezel and Aziz 2017a; Formoso et al. 2002), often devised for particular purposes, such as production planning and control (Brady 2014) or material supply (Costa and de Burgos 2015; Arbulu 2008). Even in manufacturing, the introduction of visual devices is often viewed as something intuitive and based on common sense, without considering the demand

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for information in a systematic way or the mental models of potential users (Beynon-Davies and Lederman 2016).

Recent research has explored how emerging information and communication technologies (ICTs) can replace or facilitate existing conventional VM systems on construction sites, especially due to advancements in building information modeling (BIM) (Tezel and Aziz 2017a). Gurevich and Sacks (2014) pointed out that ICTs can help overcome the difficulty of visualizing workflows. This is particularly useful at the finishing stage of building projects, when building components (e.g., walls, slabs, and roofs) create visual barriers. Although a wide range of ICTs can potentially be used to improve process transparency, such as BIM, mobile computing, laser scanning, and augmented reality (Tezel and Aziz 2017a), most applications developed so far support the work of individual managers or inspectors, instead of creating an information filed for production crews, as suggested by Greif (1991). According to Dave et al. (2016), a number of advanced ICT tools to support visual management have been successfully devised, but these are still in the early stages of implementation.

Nicolini (2007) states that the implementation of visual devices often requires a great deal of nonvisual work. In other words, creating a transparent environment requires some managerial tasks that might not involve any kind of visual device, such as processing and analyzing information and devising improvement measures (Nicolini 2007). This is particularly important because VM is not an end in itself. Instead visual devices are a means to improve the performance of production systems. Despite its importance, previous research on VM in construction often neglect nonvisual work.

Moreover, there are also opportunities for obtaining a better understanding of visual management by exploring similar concepts and approaches that have been investigated in other fields of knowledge, such as information visualization and knowledge visualization in the field of knowledge management (Eppler and Burkhard 2007), visual languages in the field of visual communication and computing (Zhang 2012; Eppler and Bresciani 2013), visual perception in the field of neuroscience (Moore 2001), and work interface design in the field of ergonomics (Tezel et al. 2016).

Some studies from other areas also emphasize the limitations of VM, including the social, cognitive, and emotional risks of visualization, such as ambiguity, inconsistency, visual stress, and collaboration inhibitors (Bresciani and Eppler 2008). Investigating those limitations also presents an opportunity for improving the theoretical understanding of VM.

This article proposes a model for devising visual management systems, understood as sets of visual practices that should be integrated in managerial processes. This model is meant to be a prescriptive contribution, i.e., it should be used as a reference for companies that intend to develop or refine visual management systems to support production management in construction projects. A secondary objective of this research work is to contextualize and extend the understanding of concepts related to visual management in construction using knowledge that is well established both in operations management and from other relevant fields of research.

Implementation of Visual Management in Construction

Implementing VM in construction sites poses additional challenges in comparison to manufacturing: (1) construction sites are changing environments where many crews move continuously; (2) the site layout undergoes several changes throughout the project, depending on the type of materials being handled, demanding an intense effort to update and relocate the necessary set of visual devices; (3) construction sites are relatively large places where different crews spread out; and (4) nonremovable visual barriers are incorporated into the working environment as the facility is being constructed (Formoso et al. 2002).

A wide range of VM practices have been used in manufacturing, some of which have been adapted to construction sites. Some visual devices are relatively simple, such as information boards containing procedures, drawings, and performance measures, while other practices require extensive planning, a certain level of readiness, and stability within the production system (Tezel et al. 2015), such as *kanban* systems for pulling production or material supply, *heijunka* boards for leveling production, 5S programs for housekeeping, and *andon* systems for managing the help chain.

Galsworth (1997) classifies visual devices in four categories, according to the degree of control exerted by each of them: (1) visual indicator: information is simply displayed, and compliance or adherence to its content is voluntary (e.g., safety advice boards, working instructions); (2) visual signal: this kind of visual device first catches one's attention and then delivers its message (e.g., sirens, call lights); (3) visual control: this is an attempt to impact behavior directly by structuring or building a message directly in the physical environment (e.g., speed bumps, pathway borders); and (4) visual guarantee (*poka-yoke* device): this is designed to make sure that only the right thing happens (e.g., electronic circuits that prevent movement of lifts when the door is open). Ewenstein and Whyte (2009) proposed another classification of visual devices based on two simple, but relevant, categories: (1) inability to be changed ("frozen") or (2) able to be change ("fluid"), often as part of collaborative processes. These categories correspond, respectively, to static and dynamic visual devices, as suggested by Bititci et al. (2015).

It has been pointed out that VM is the predominant mode of communication within organizations that seek to reinforce employee autonomy. In a traditional work environment, control and knowledge tend to be centralized, while in a transparent environment the network of information is independent of the hierarchical structure of order giving (Greif 1991). Therefore, employees are allowed to control execution by comparing current conditions to given production objectives (Steudel and Desruelle 1992). According to Greif (1991), in a well-designed visual management system, information must be incorporated into the process and should be as close as possible to workers. In this context, information should be shared only when and if it is retrieved by a user (Galsworth 1997).

Furthermore, visual management may increase the involvement of workers in continuous improvement efforts (Bernstein 2012) because it allows for rapid understanding of and response to problems (Bateman et al. 2016). Process control is simplified, reducing the propensity to commit errors and, most certainly, increasing the visibility of errors (Koskela 1992).

Tezel et al. (2015) identified some opportunities for improving the implementation of visual management in the construction industry, including by (1) increasing awareness on the wide range of VM devices that are applicable on construction sites instead of using only static visual indicators; (2) increasing the degree of involvement of the workforce in devising and retaining visual management systems rather than using a top-down approach in the implementation process; and (3) investing in work-force training, logistic preparations, and site arrangements when implementing complex VM tools.

Contributions from Other Fields of Knowledge

The fields of neuroscience and neuropsychology provide the theoretical foundations of visual thinking, defined by Ware (2008) as "a series of acts of attention, directing eye movements and adjusting our pattern discovery circuits." Spagnol and Li (2015) suggest that illustrations have a more important role in cognitive memory than words and assist in communicating complex messages with simplicity. Therefore, visual thinking is concerned with the mechanism of human visual perception and how visual representations stimulate cognition. The recognition of patterns depends on a network of paths in the brain that allow us to connect what we see with what we already know (Ware 2008). Indeed, Moore (2001) points out the importance of previous experiences and mental models of users in the desired interpretation of visual information.

The literature from social and behavioral sciences emphasizes the relationship between visual communication and design and education, culture, society, and the training of skilled and creative professionals. Over time, the design of visual communication, which was developed along with a number of artistic and design movements, has become an indispensable part of mass communication (Sekeroglu 2012). In relation to culture and society, Dur (2014) states that people's beliefs, behavioral patterns, values, and traditions can influence visual communication. Therefore, establishing effective communication requires the designer to use a visual language that the target audience can understand. In this context, it is important to make effective visual use of cultural codes by first learning, understanding, and analyzing the culture of the society in question.

Visual expressions, such as pictograms, are in fact a conceptually rich form of communication and have played a key role in facilitating communication between people (Sekeroglu 2012). This form of communication has been related to the concept of visual literacy, which refers to the use of images for the purpose of communication, reflection, learning, construction of meaning, creative expression, and aesthetic pleasure (Avgerinou and Ericson 1997).

This capacity for visualization can be developed at either the individual or the institutional level (Mange et al. 2015). At the individual level, the ability to visualize depends on skills that must be developed starting in childhood (Sekeroglu 2012). At the institutional level, Kerr et al. (2013) describe three visual elements that are indispensable for the development of effective devices for visual communication: (1) attractors, which encourage the public to take note of the system in the first place; (2) sustainers, which keep people involved during an initial meeting; and (3) relaters, which help the continuing relationship to grow so that the people can return to the artifact on future occasions.

The field of visual languages and computing is concerned with classes, frameworks, and methods for conceiving visual languages and representations (Bottoni et al. 1998; Costagliola et al. 2002). Recent publications address the issue of knowledge visualization, management visualization, and collaborative dimensions of visualization (Zhang 2012; Eppler and Bresciani 2013; Yusoff and Salim 2015; Alexander et al. 2015). Those topics have been the focus of some research studies on the use of ICTs for visual management in construction, including the visualization of construction operations (Kamat et al. 2011), workflows (Sacks et al. 2009), and project performance (Lee and Rojas 2013).

Ergonomics is another field that has produced research related to VM (Tezel et al. 2016), such as the assessment and design of visual devices or subsystems considering constraints concerned with organizational goals, human psychology, and physical abilities (Lehto and Landry 2012). Although VM-related phenomena are often similar to those addressed by other fields of research (e.g., visual thinking and visual language), research on ergonomics is based on a different theoretical framework. The main contributions of ergonomics to VM are related to a detailed analysis of how visual devices work, such as the impact of dynamic features for hazard control (Duarte et al. 2014), factors that affect the effectiveness of warnings (Kim and Wogalter 2015), and the effectiveness of coding in terms of color, shape, texture, size, location, and label (Lehto and Landry 2012).

Zhang (2012) claims that visual communication is a key topic in the framework of managerial aesthetics, an emerging multidisciplinary subject that emphasizes the critical roles of visual elements in management. Eppler and Bresciani (2013) highlight how visualization can enhance collaborative activities in organizations, besides the cognitive and communication roles. Those authors report the use of conceptual diagrams, metaphors, or sketches as collaboration catalysts to facilitate a variety of tasks, from idea generation to decision-making, planning, knowledge sharing, and learning.

According to Eppler and Burkhard (2007), the creation and effective transfer of knowledge through visualization involve five perspectives: (1) what kind of knowledge is visualized (content); (2) why this knowledge should be visualized (purpose); (3) for whom this knowledge must be visualized (target group); (4) in what context this knowledge should be visualized (communicative situation: participants, place, media); and (5) how knowledge can be represented (method, format). These issues are connected to the hidden work involved in visual management.

Overall, the literature review on other fields of knowledge highlighted a list of relevant topics related to VM that have not yet been addressed by the construction management community, such as concerns with visual identity, social and cultural issues, association with mental models, and the creative process of developing visual devices. It is also worth noting how visual devices are used for different purposes in comparison to production management, in which the aim is process standardization and rapid detection of deviations. By contrast, in some social science–related fields, the role of visual devices is concerned with stimulating creativity among team members, joint processing of information, and collaboration.

Research Method

Research Approach

Design science research was the methodological approach adopted in this investigation. It is a way of producing scientific knowledge that involves the development of an artifact (or a solution concept) to solve classes of problems (Holmström et al. 2009). The artifact developed in this investigation is a model that contains prescriptions for devising visual management systems to support production management in construction projects.

The research approach was exploratory and inductive, i.e., the model emerged during the research process, based mostly on qualitative data. This is a type of research strategy that fits the solution incubation stage of design science research, as suggested by Holmström et al. (2009). However, an important limitation of this investigation is that it was not possible to test the model in an organizational context.

This investigation was divided into four stages (Fig. 1). In the first three stages, different types of empirical studies were undertaken, providing a distinct contribution to the development of the model. Stage 4 consisted of the development of the final version of the model and a reflection on the main contributions of this investigation. Open interviews and unstructured direct observation in construction sites were the main sources of evidence used at the beginning of the investigation. In later stages of the research study, as the main elements of the model were devised, data collection became more structured and systematic.

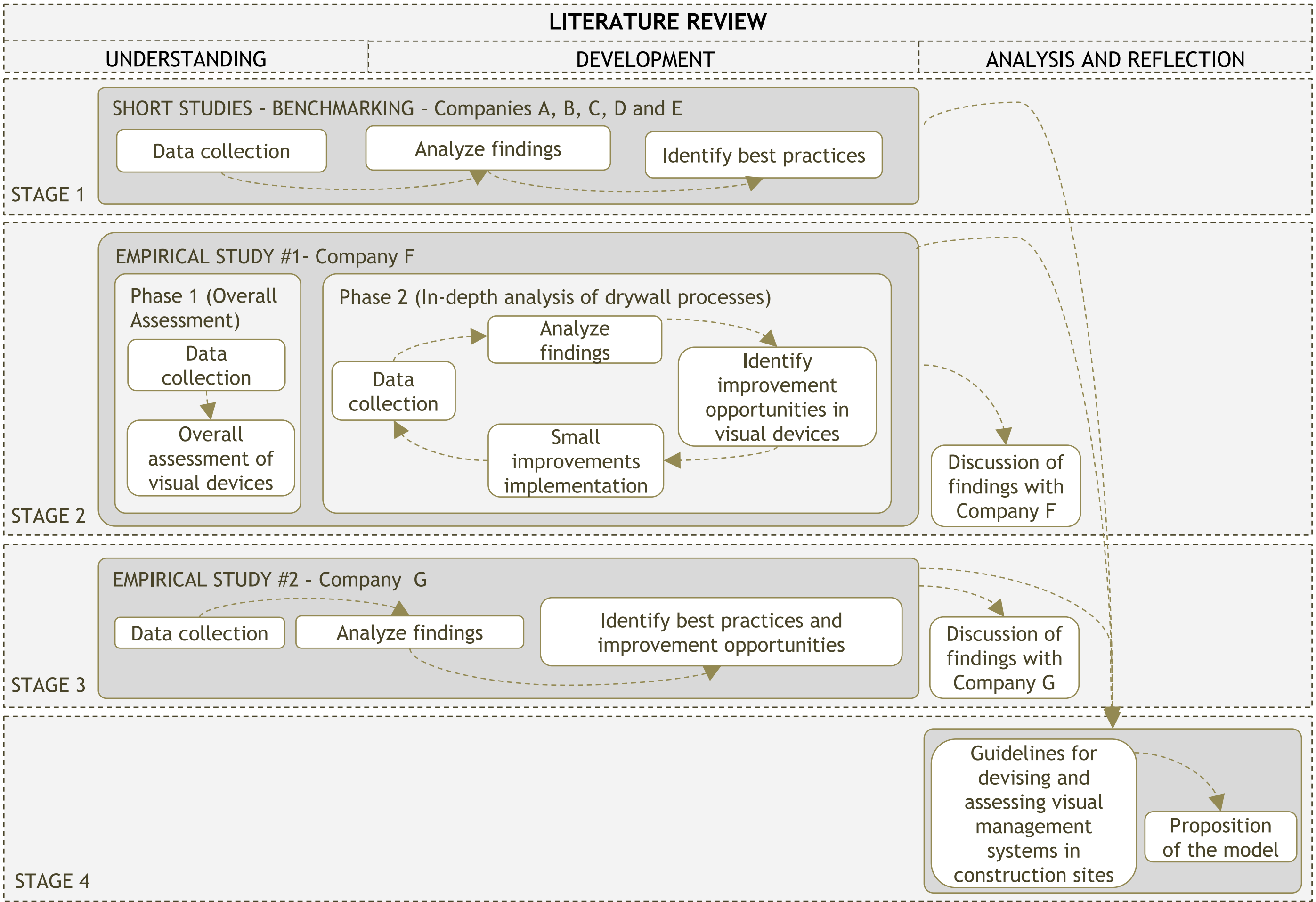

Fig. 1. Research design.

Stage 1

The first stage consisted of a set of benchmarking studies, in which the visual management systems of five companies outside the construction industry were analyzed. Four of the companies are from the manufacturing industry, and the fifth one develops digital solutions (Table 1). Four of them are branches of multinational companies that have well-established lean-based improvement programs, and the fifth company was part of a supply chain that was very advanced in terms of implementation of lean concepts. These companies were chosen because they had advanced visual management systems, some of them well integrated in managerial processes. Although it is not possible to state that those companies can be considered the most advanced ones in their sectors, they were certainly more advanced in VM than most construction companies and were considered to be suitable for a benchmarking exercise in this research study.

A set of VM best practices was identified and analyzed in each company, so that these could be used as a reference for critically assessing practices found in the construction sites of the two construction companies involved in Stages 2 and 3 of this investigation. Each study involved direct observation of production facilities, and one interview was conducted with a manager directly involved in the development or implementation of the visual management system.

Table 1. Industrial sectors and interviews carried out in benchmarking studies

Company	Industrial sector	Interview
A	Gear and couplings	Industrial manager
B	Rigid and flexible packaging	Process engineering analyst
C	Agricultural machinery and equipment	Process engineer
D	Soft drinks	Continuous improvement assistant
E	Digital solutions	Head of operations

Stage 2

The second stage of the research project consisted of an empirical study carried out in a construction company (referred to as Company F), in which the visual management system adopted at one construction site was assessed. This is a large house building company from Brazil that has branches in 17 different states. Company F develops and builds commercial, residential (mostly for the higher middle class), and, more recently, health-care projects. This firm was chosen because it is well known as a leading company in Brazil on the implementation of lean production concepts and practices. In fact, it was included as one of the best practicing companies of visual management in Brazil in a report produced by Tezel et al. (2010). The empirical study was carried out in a health-care construction project, a short-stay hospital located in Porto Alegre.

This project was chosen because it was considered to be the most advanced with respect to visual management practices in the Porto Alegre Metropolitan Region.

The aim of the empirical study was to understand the underlying ideas behind the visual management practices implemented by Company F, as well as the main barriers to making those practices effective, based on a comprehensive evaluation of the visual tools adopted at a particular construction site. This empirical study was divided into two phases.

The first phase consisted of an overall assessment of a set of visual devices that had been implemented at the construction site, considering the four categories of visual device proposed by Galsworth (1997): indicator, signal, control, and guarantee. Some visual devices were excluded from this assessment: (1) those located in the site management office, mostly used for production planning and control, and (2) very simple, static visual indicators (e.g., safety warnings) because the main focus of this assessment was the support provided by visual management in the execution of construction processes.

Six site visits were undertaken, in which 37 types of visual devices were assessed. A protocol was devised for guiding data collection and processing, including the following information for each visual device:

1. A brief description of the content of the information displayed;
2. Function(s) performed by visual devices: alert, support execution of activity, identify, inform, plan, control, and guarantee;
3. Location of visual device;
4. Role of information displayed: what, when, where, how, how much/many, why, and who;
5. People in charge of devising and updating visual devices (information providers) and target group (information users), e.g., site management team, foremen, subcontractors, external departments, and workers;
6. Source of information displayed in visual device;
7. Managerial area supported by visual devices (e.g., planning and control, quality, safety, logistics, waste detection);
8. Whether it was a standard practice in the company or an individual initiative of site management;
9. Whether the visual device was static or dynamic; and
10. Frequency with which information was updated.

These data were stored in a spreadsheet, and a picture was taken for each visual device, when possible. Based on those data, some quantitative figures were calculated, such as the percentage distribution of those 37 visual devices according to the functions performed (Fig. 2), type of information displayed (Fig. 3), information providers and users (Fig. 4), and whether the device was dynamic or static. It is worth emphasizing some limitations of the quantitative figures, as these were influenced by the criteria adopted for excluding visual devices from the analysis, and also by the interpretation of how the visual devices were used, which were based on multiple sources of evidence, i.e., direct observation, analysis of documents, and interviews.

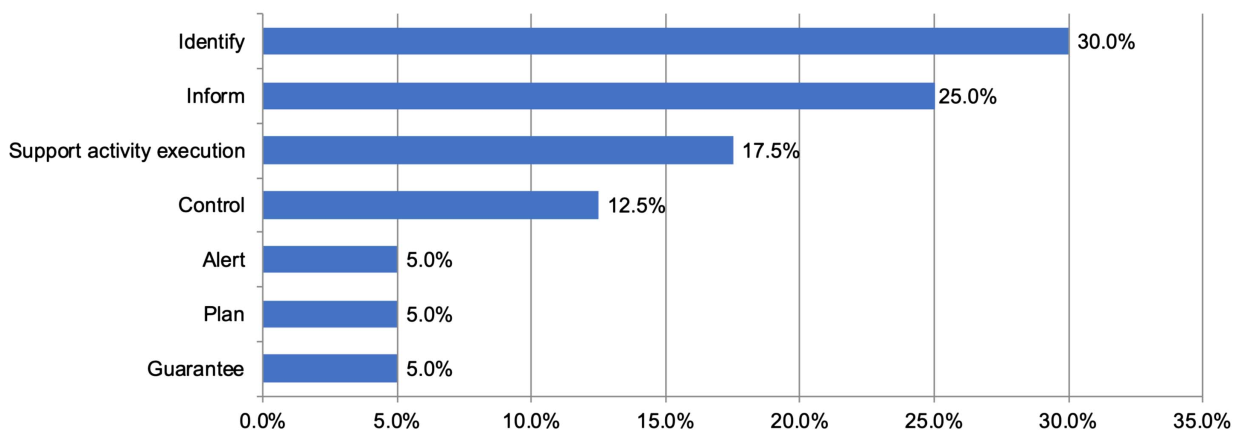

Fig. 2. Classification of visual tools according to functions performed (percentage of visual devices).

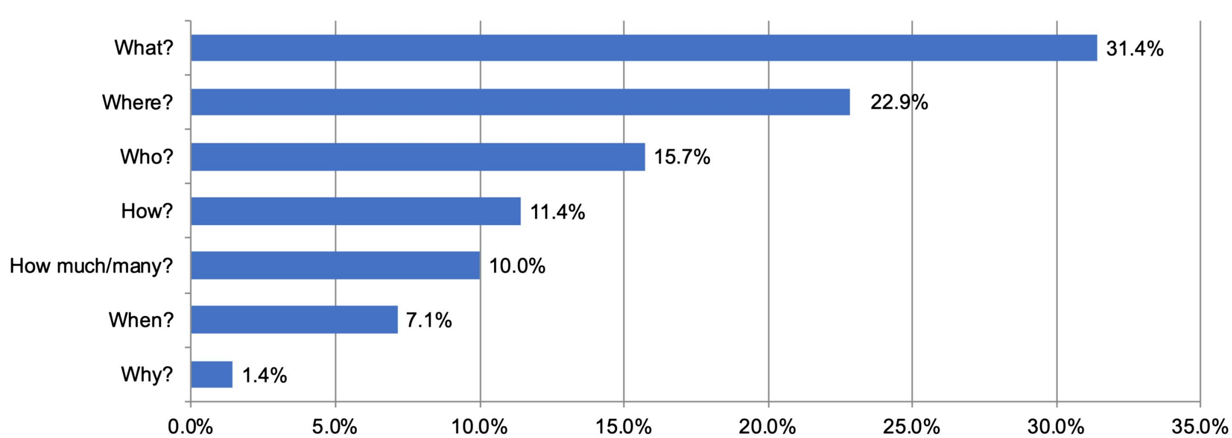

Fig. 3. Classification of visual tools according to type of information (percentage of visual devices).

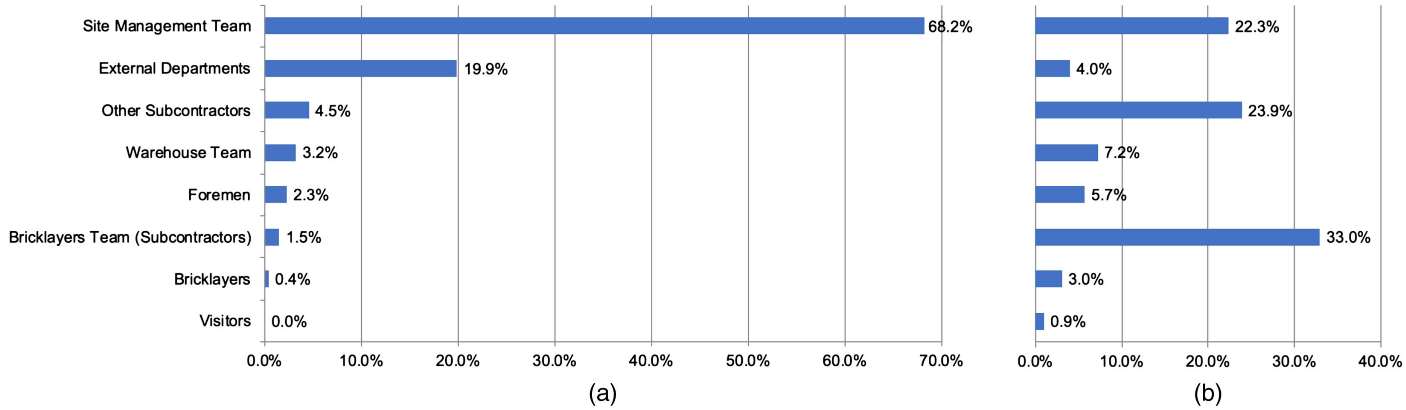

Fig. 4. Participation of people as (a) information providers; and (b) users of visual devices (percentage of visual devices).

The main outcomes of this phase were the identification of improvement opportunities related to the existing visual management system and an assessment of the degree of integration of the visual devices in existing managerial systems.

The second phase consisted of a detailed analysis of the visual management devices that supported the installation of drywall internal partitions. The main reasons for choosing this process were that (1) it played a key role in site installation due to the large number of interdependencies with other processes and that (2) most components were industrialized, and this process had a relatively short lead time, allowing the identification of improvement opportunities that could be rapidly implemented.

Multiple sources of evidence were used in the analysis of the installation of dry-wall partitions, including direct observation of the whole process, from the delivery of materials to the final inspection; interviews with workers; and analysis of documents and of the *kanban* used for pulling material supply. Based on this analysis, some improvements were implemented in the process, including changes in visual devices, and the results were monitored by the research team. Some metrics were used for assessing the impact of those improvements, including the percentage of material waste and time spent in material supply.

These are the sources of evidence used in both phases of this empirical study: (1) interviews (40–60 min) with two site managers, the foreman, a technical assistant, interns, four workers involved in material supply, and two warehouse keepers; (2) direct observation of the construction site (13 visits), including visual devices and production operations; (3) measurement of time spent in material supply; (4) analysis of documents (conventional production plans, visual schedules, inventory sheets, standard operating procedures, and flowcharts) and secondary data (amount of wastage produced); and (5) participant observation in a planning meeting. The results of this study were discussed with representatives of Company F in three meetings and two seminars.

Stage 3

The third stage of the research project consisted of an empirical study carried out in a company from Fortaleza, Northeastern Brazil (Company G), which develops and builds upper-middle-class residential as well as commercial building projects. This company was chosen for also being a leading construction company in the implementation of lean production concepts and practices in Brazil. It was also mentioned as a best practice company on visual management in Brazil in a report produced by Tezel et al. (2010).

This second empirical study had a descriptive character and was based on data collected in four construction sites: three residential projects and one healthcare project. Unlike the study carried out in Company F, this empirical study was focused on a small set of practices with the aim of exploring the role of visual devices in managerial routines, especially in terms of supporting coordination and collaboration. Such practices were analyzed as VM subsystems, each one of them involving both visual and nonvisual work and one or more dynamic visual devices.

A protocol was also devised for data collection and processing, including the following information: brief description of visual subsystems; main purposes; information providers and users; and the main impacts (based on the perception of managers). Due to the small number of visual subsystems and limitations in resources for data collection, no quantitative measures were used in this analysis.

Sources of evidence used during the second empirical study were as follows: (1) interviews (60–120 min) with five production managers, one innovation manager, one safety technician, two design managers (one of the involved in the customization of housing units), and the material supply and logistics manager; (2) direct observations at the construction sites (six visits), including visual devices and production operations, and in the head office of the company (three visits); and (3) analysis of documents, such as plans, standardized worksheets, visual schedules, inventory sheets, and flowcharts. Moreover, some data collected from participant observations were also used, as one of the authors worked for a 5-year period as an innovation manager in Company G.

Stage 4

At the end of the research project, data from all empirical studies were analyzed and compared, and the final version of the model for devising visual management systems was built. Moreover, a set of guidelines for carrying out the tasks involved in the conception of those systems was proposed.

Research Findings

Stage 1: Benchmarking Studies

Some VM best practices relevant for the construction industry were found in all five benchmarking studies. First, in all five companies the visual devices were extensively used to support rituals of daily meetings that usually take place in the morning, before the start of the work shift, and last from 5 to 30 min. The agenda usually consists of follow-up on the activities carried out during the previous day, problems that had occurred during the most recent shift, the current day's schedule, analysis of weekly indicators, action plans for performance improvement, and incidents. These meetings were highly collaborative and often involved not only people engaged in production, but also those from other sectors, such as quality management, planning, safety, and logistics. These companies also used visual charts made visible to all workers and kept information available and accessible at a glance to users, providing rapid feedback, as suggested by Bateman et al. (2016).

Another best practice was to use visual devices to support the standardization of both processes and operations, including non-value-adding activities, such as inspection, logistical operations, and accident prevention measures. Different types of information were included in those visual devices, including standardized worksheets, checklists, and performance metrics.

Some traditional practices from the Toyota Production System (Ohno 1988; Womack et al. 1990), such as *kanban* and *andon*, were used by most companies. *Kanban* was both used for pulling production as well as the supply of materials, mostly in a very decentralized way, i.e., the operators themselves were in charge of placing necessary information. In some cases, *kanban* boards were used for controlling work in progress and the pace of work. *Andon* systems were used for the early detection of abnormalities by giving workers the autonomy to pull the help chain.

Finally, high importance was given by the five organizations to the use of A3 reports as a tool for problem solving and communication. All of them adopted A3s to report production and administrative problems and disseminate the implementation of improvements, in a very simple and direct way. In three of the companies, the A3 chart had standardized sections.

The main contributions of the benchmarking studies to the development of the model can be summarized in a set of preliminary guidelines for designing and implementing visual management systems: (1) visual devices can be used not only as a form of communication but also to support collaboration; (2) at the level of the workforce, visual devices should make information available and accessible at a glance, providing rapid feedback; (3) workers not only should be regarded as users of visual devices but must also get involved in producing information to be disseminated; (4) visual devices should support the standardization of both value-adding and non-value-adding activities; and (5) visual management must be used not only to communicate standards for routine work but also to disseminate the implementation of improvements.

Stage 2: Company F

Overall Assessment of Visual Management Devices

Figs. 2 and 3 present the percentage distribution of visual devices, according to the functions performed and type of information provided, based on the classification proposed by Eppler and Burkhard (2007). Fig. 2 indicates that more than half of the visual devices performed functions of identifying or signifying something, which refers to the most basic types of visual tools (indicators or signs). Only 12.5% of tools were used for data or activity control functions, and only 5% were intended to guarantee an action by using an error-proof device. Hence, the adoption of more powerful tools, such as visual controls and guarantees, was identified as an improvement opportunity in terms of increasing the impact of visual devices in work standards.

Regarding the type of information displayed, more than half of the devices were also intended for basic identification or location (Fig. 3). A large percentage (31.4%) of devices portrayed information that responded to a "what?" question, followed by devices that answered "where?" (22.9%) and "who?" questions (15.7%). One surprising result was the very small percentage (1.4%) of visual tools associated with a "why?" type of question. Answers to this type of question usually relate to the reason or purpose for a particular action or attitude, which often refers to the company's beliefs, values, and culture. The lack of this type of information on visual devices can be related to the typical role of task execution played by the labor force in the construction industry, assuming that it is not necessary for workers to know much about the purpose of things.

The relatively low level of participation of workers in visual management systems was also made evident by the source of the information to be disseminated through visual devices. The percentage distribution shown in Fig. 4 indicates that most information displayed on visual devices was produced by the site management team. Workers were rarely involved in the conception or updating of visual devices, despite the fact that these had useful information for task execution. Consequently, the site management team had to spend a considerable amount of time in production control activities, which is at odds with the idea that process transparency should be used to increase the autonomy of the labor force.

In general, the number of visual devices observed in this construction site was much larger than what is usually found at ordinary sites. However, a large percentage of those devices supported only two managerial processes. Around half of them were related to production planning and control, including productivity evaluation tables and daily worksheets for laborers. Twenty-two percent of the devices had to do with quality management, such as work standards, inspection sheets, and quality policy panel, although none of them displayed data on defect rates or abnormalities. In general, visual devices were fairly well integrated into the production planning and control and quality management processes.

However, some information deficits were identified in other managerial processes, such as safety management, waste detection, and logistics management. Regarding safety, although workers were encouraged to report near misses, most visual devices were static and did not provide much support to solve problems or to mitigate complexity. The ones that were dynamic only displayed reactive data, e.g., accident rates and action plans after accidents.

The results presented here indicate that existing visual management systems can be improved in two complementary ways. Overall, it seems to be important for Company F to seek a balance with respect to the use of visual devices among different managerial processes and to use visual devices that offer more support for production control and improvement. It would be better to have a smaller number of dynamic visual devices that effectively support decision-making and encourage reflection and collaboration, rather than having a large number of devices, most of them with a low impact on production management.

Improving VM in the Installation of Dry-Wall Partitions

Company F had devised a VM subsystem for this process, combining several visual devices: physical prototype, templates, inspection sheets, standard operating procedure flowchart, *kanban* for supplying materials, visual schedule for each floor, and material control sheets. There were several good practices in this subsystem: most visual devices were dynamic and were well integrated into the process. For instance, the physical prototype was used, among other things, to adjust the amount of materials for the *kanban* subsystem. By contrast, some problems were detected in the *kanban* subsystem: (1) cards were sometimes used simply as inventory distribution sheets and (2) some cards contained insufficient information to be understood by the material supply team. This caused time losses

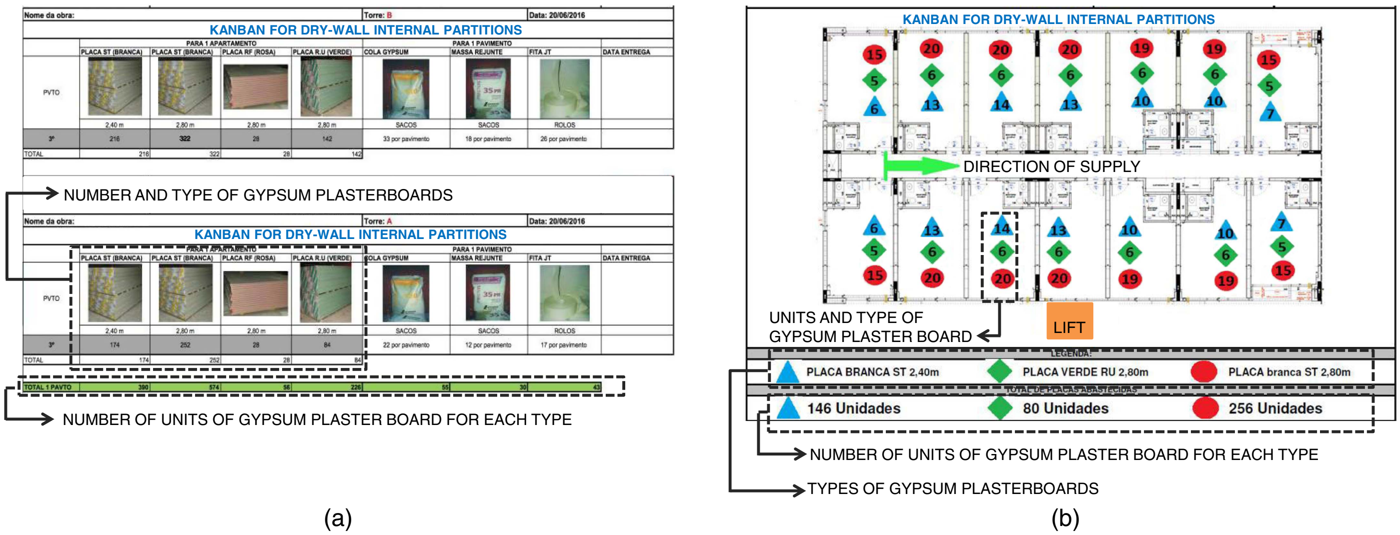

Fig. 5. *Kanban* for supply of dry-wall components: (a) old version; and (b) new version.

and productivity reduction, as components were placed in only two spaces throughout the entire floor and later transported to each room.

After some discussions, the production management team decided to change the *kanban* subsystem. Fig. 5 presents two versions of *kanban* for delivering dry-wall plasterboards. The main changes introduced were the adoption of small delivery batches, the indication of the flows in material supply, and the use of very simple symbols for indicating the number of components to be delivered at each work location. The design of the new card involved the research team, site managers, and the material supply team. The number of panels used per floor as well as information related to colors and shapes was included in the lower part of the *kanban*. Based on this, the company started to supply the exact amount of gypsum plasterboard for each production batch (a commercial or clinical room).

Despite some problems related to unfinished work and material leftover, substantial improvements were made. As the company had monitored the amount of material waste due to its environmental policy, a 6% reduction in gypsum plasterboard waste was detected after the changes introduced in the *kanban* subsystem. Regarding the time spent in supplying dry-wall plasterboards, based on a 5-week monitoring of deliveries (typically twice a week), productivity was incrementally increased due to the reduction in the time spent counting components and better organization of inventories. However, even after the changes in the *kanban* system, the material supply team had to spend 33% of its time waiting for the panels to arrive in the elevator due to interference from other material supply operations. Thus, more time should be spent on standardizing and coordinating logistics operations.

Main Contributions

Despite the fact that Company F is considered a leading company with respect to implementation of visual management in the Brazilian construction industry, some opportunities for improvement were noted: (1) visual devices should be used to support routine collaborative meetings; (2) more visual devices should be implemented at the operational level, providing information to workers at a glance; (3) more emphasis should be placed on the use of visual management for eliminating non-value-adding activities, including transportation, setup, and inspection; (4) the use of some visual devices, such as *kanban* and *andon*, should be more decentralized; and (5) some visual devices could be used for reporting problems and disseminating the successful implementation of improvements.

Therefore, the main contributions of Stage 2 to the development of the model are concerned with the need to design and revise visual devices for production management in a systematic way, following a number of steps: (1) understand existing problems in production management; (2) identify the needs of potential users, as suggested by Galsworth (1997); (3) define the expected actions from the use of visual devices, so that they are fully integrated into managerial processes; and (4) define visual device attributes (e.g., content, format). Those steps are consistent with the five perspectives proposed by Eppler and Burkhard (2007).

Stage 3: Company G

Overall Assessment of VM Subsystems

Seven VM subsystems were chosen to be analyzed in this empirical study. These are briefly described in Table 2, including the main purpose, users, people in charge of inputting or updating information, and main impacts. Those subsystems were considered to be advanced because they were successful in terms of supporting decision-making and task execution, i.e., the visual devices were well integrated into managerial routines. Some examples of visual devices are presented in Figs. 6–9.

The customization choice board (Fig. 6) is a visual device that was developed by the customization coordinator of the company for keeping updated information about the choices made by final customers. That information is made available to different departments of the company, including design management, material supply, and production management. There are several customization options in most projects undertaken by Company G, as shown in the example presented in Fig. 6, such as alternative floor plans, different options for floor tiles, wall finishings, and kitchen and bathroom fittings, among others.

Fig. 7 presents a constraint analysis board for communal areas. It contains the layout of the infrastructure to be built, a division into small batches, a schedule of activities, and a list of constraints. This visual device is placed in the room where planning and control meetings take place, and it is used to support collaboration every time a look-ahead plan for communal areas needs to be made.

Table 2. Visual subsystems of Company G

Visual subsystem	Description	Main purpose	Responsible for inputs and updating information	Users	Impacts
Customization choice board	Gathers information related to customization choices in residential units; color coding is used to communicate quickly the choice made (e.g., green for standard first choice, yellow for standard second choice; red for excluding a component) (Fig. 6)	• Acts as a boundary object • Useful for exchanging information and collaboration between distinct departments • To facilitate communication with customers	• Customization manager	• Customization manager • Site management • Material supply and logistics management	• Improved communication between company and clients since choices are made explicit • Site engineer and production supervisors can prepare weekly plan and manage information related to material supply • Material supply and logistics manager can quantify amount of material to be purchased
Visual performance and planning boards	Visual boards contain main indicators for each area and a plan of activities produced by using Post-its, containing "to do," "doing," and "done" activities All construction sites also have visual performance boards with the main indicators, look-ahead, and weekly work plans, as well as other key devices elaborated by other departments of the company Visual performance and planning boards are flexible enough to represent their owners' mental model, i.e., they structure the board with information that purposely reflects the way they understand and participate in the process	• Makes visible invisible process attributes (Koskela 1992) • To serve as visual clue • Summarize information from different sources • Improve communication among teams • Facilitate learning and knowledge management for new employees, who quickly understand key controls and the importance of transparency Induces routine of looking at information and acting upon it	• Each department is responsible for its own board and for inputting information to construction site boards • Site manager	• Several head office departments • Site management	• For many departments, it is a way of getting an overview of the area and the needs of other departments • The use of Post-its has helped in balancing the activities of the team; each color corresponds to a professional: "when you see many Post-its of a single color, this person is overloaded, then a new distribution of tasks takes place" • At construction sites, the board organizes some key information; spaces available on board also indicate what information is missing
Constraint analysis board for communal areas	A map containing landscape and architectural design of communal areas; this map supports the process of identifying constraints in a collaborative way (Fig. 7)	• Support collaboration between site management and subcontractors • Help identify look-ahead constraints and interference between processes • Help identify critical areas (time-consuming or complex services)	• Site management	• Site management • Subcontractors	• Visualizing common areas daily on wall, rather than in drawings, encourages site management team to think often about list of constraints • Subcontractors can be easily engaged in look-ahead planning
Standardized worksheet	Standardized worksheets (or cards) are produced when a new standard is proposed or improved and tested. Each sheet contains the day, shift, schedule, tasks, and production batch for each task; this standard contains not only value-adding activities, but also setup and inspection activities and waiting time (Fig. 8)	• Support implementation of newly standardized operations • Facilitate understanding of new sequence of operations for employees (some pictograms are sometimes used when employees were illiterate) • Engage production teams in process of continuous improvement; • Facilitate efficient communication of expectations of jobs and inspection goals	• Innovation (lean and green) manage	• Production managers • Production teams	• "The introduction of these cards into the routine of employees has made them more motivated and committed because they know exactly what is expected of them" • The use of the tool is also relevant to process control by production supervisors, as well as to the definition of the production cycle time • Production control and performance measurement are made easier for employees and supervisors

Table 2. (*Continued.*)

Visual subsystem	Description	Main purpose	Responsible for inputs and updating information	Users	Impacts
Kanban	*Kanbans* are operated by production crews (workers). Production teams place information on *kanbans* about the quantity and type of materials, delivery location, and team name. For some materials (e.g., mortar), *kanbans* are placed in *heijunka boards*, and a specific time is defined. There are also *heijunka* boards for blocks, ceramic tiles, plaster bags, and pre-fabricated material. The person responsible for material flows manages this panel and the supply at all workstations	• Facilitate better communication • Clear information flow • Facilitate better planning of production • Help reduce waste • Level production • Support pull production system	• Production team	• Production teams • Mortar mixer operator • Material flow operator	• Heijunka board is useful for leveling production of materials (e.g., mortar) • Workers are motivated and committed to using *kanbans* since they receive mortar at right time • This new form of managing mortar requests has contributed to waste reduction • Reduction in time to order materials and reduction in consumption of materials
Andon	The control panel is installed in the site office and sends warnings to managers (Fig. 9). Light switches containing three buttons are installed in every floor of the building When green light is on, there are teams working on that particular floor. A yellow light means that in approximately half an hour the teams working on that floor must stop production. Finally, a red light indicates a stoppage in production. When yellow or red events occur, supervisors and engineers are called for help. They are in charge of understanding problems, help workers solve problems, propose countermeasures or possible improvements to prevent recurrence	• Inform production status for every level of project • Identify problems in production and take measures to eliminate them and prevent their reoccurrence • Give workers autonomy stop production line in face of abnormalities • Create learning effect from yellow and red events	• Site management	• Site management • Production teams • Production supervisor	• *Andon* helps to increase production efficiency since abnormalities are easily and quickly identified and the problem solved promptly • Makes communication more effective, encouraging discussion and participation of workers; this relates to autonomy to stop production when there is a problem; autonomy also affects worker motivation
Physical prototyping	A prototype is produced early in the project for the residential unit to be sold. A standard apartment is built with all finishings before the end of the concrete structure. At the end of the process, a kaizen notebook is organized with all improvements implemented	• Test execution sequences and measure duration of some tasks • Estimate quantities of materials for *kanbans* • Decide best floor pagination and define other design details • Identify interferences between different components not detected in drawings • Support collaborative processes between company, designers, and subcontractors • Create learning effect for other private units	• Site management	• Site management • Designers • Subcontractors • Project manager	• This prototype is used as a reference for the execution of other departments and also confirms design decisions that must be repeated for other units • Product prototype often results in better planning of teams, activities, and materials • Many decisions involve collaboration between company, subcontractors, and designers • Product prototype kaizen notebook is a powerful source of information that must be shared among stakeholders and support decision-making

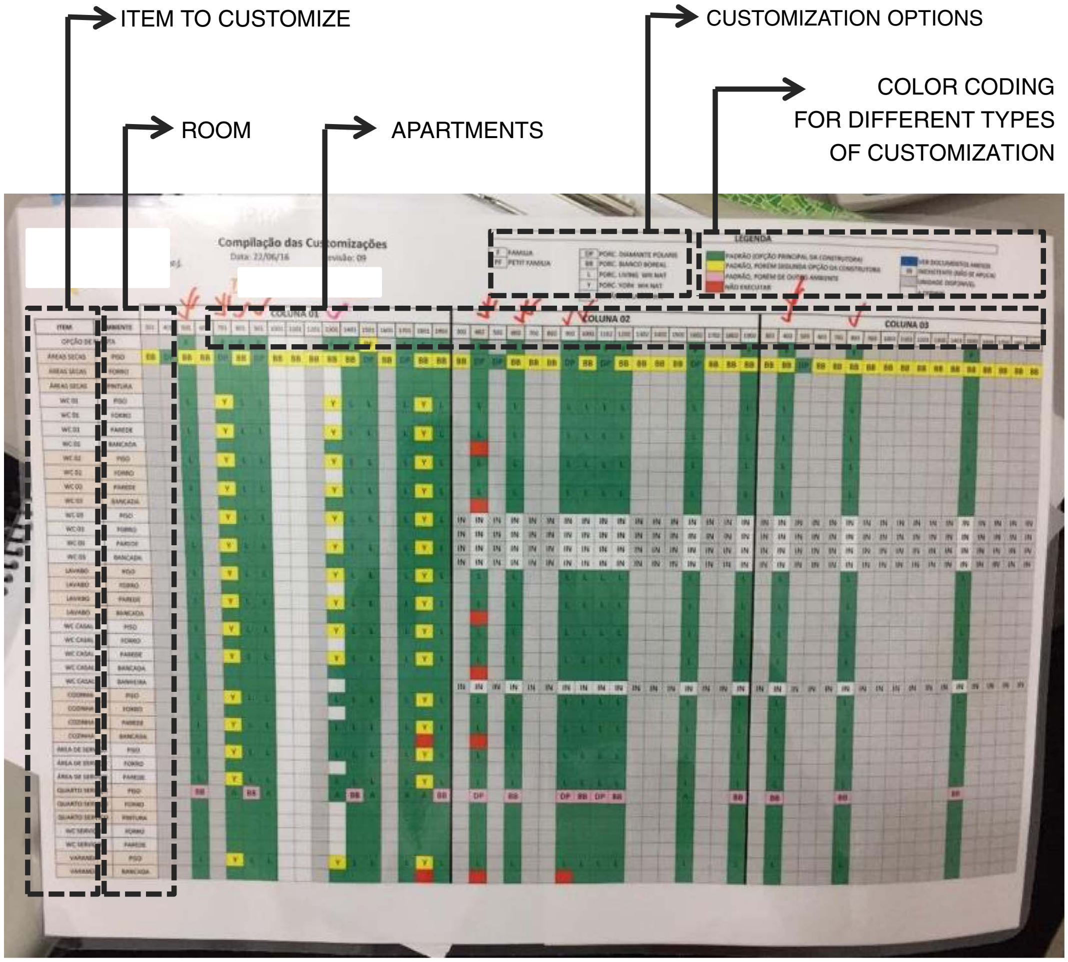

Fig. 6. Customization choice board.

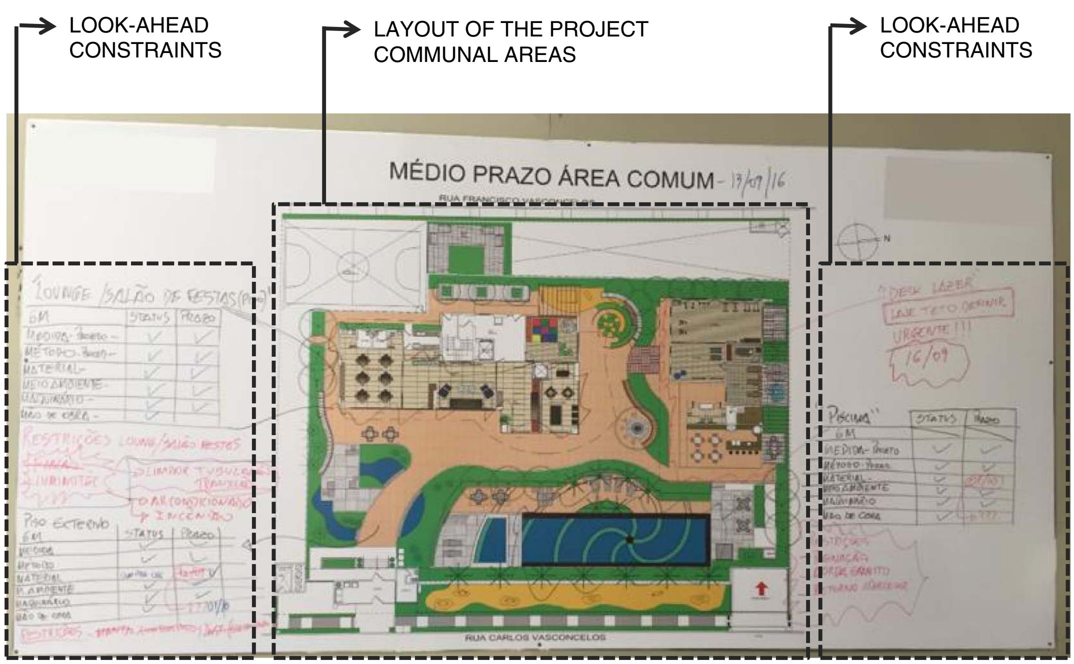

Fig. 7. Constraint analysis board for communal areas (look-ahead planning).

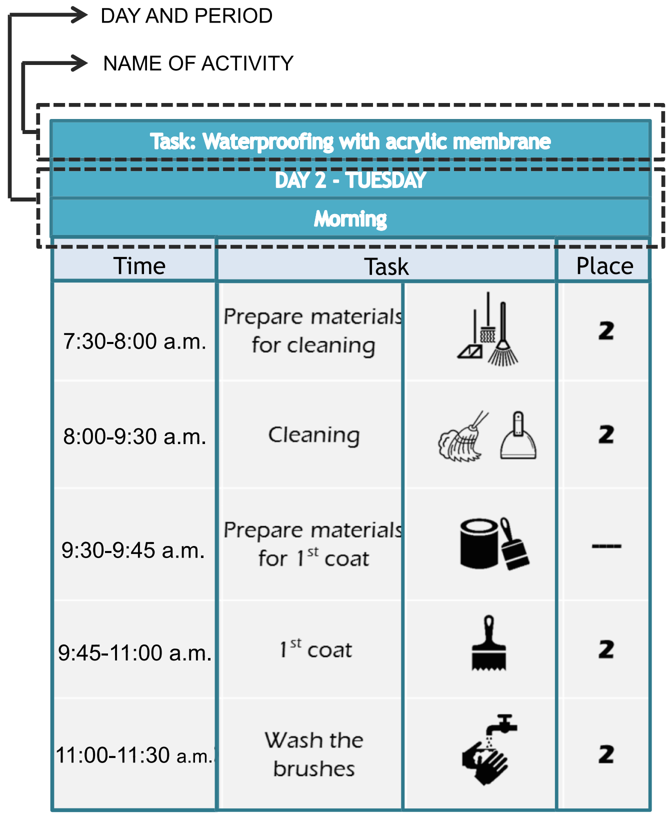

Fig. 8. Standardized worksheet.

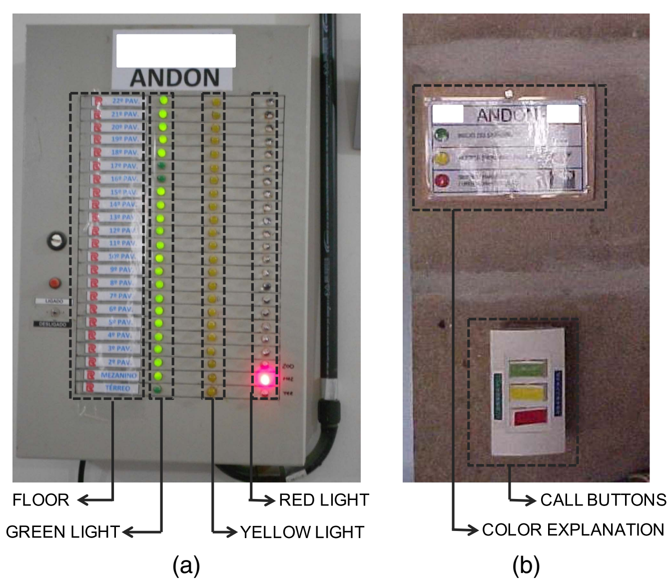

Fig. 9. *Andon* system: (a) warning board; and (b) call button.

Fig. 8 presents a standardized worksheet, which is a card that contains basic information about a set of operations, including the sequence of steps, duration of each task, and location. In Company G, this standard is usually developed or revised in collaboration with the workforce.

Fig. 9 presents an *andon* system. There are three different buttons on each floor: (1) green, if everything is fine; (2) yellow, if some help is needed; and (3) red, if a crew has stopped. The *andon* board is placed in the site office, and the lights indicate the status of each floor.

Based on a cross-analysis of the set of visual subsystems and the managerial work involved on it, these were classified into three main categories according to the degree of integration with managerial routines, named one-to-one, coordination, and collaborative visual subsystems.

In the first category, visual subsystems simply make performance measures public or offer instructions to perform a task. This is the most basic form of incorporating visual devices into processes. Information must be easy to understand and process at a glance. This may involve color coding, sound, physical barriers, icons, and other visual devices that are effectively incorporated into a process. This is the case of standardized worksheets and the *andon* and *kanban* subsystems, which establish a clear communication channel between sender and receiver. Collaboration may exist in the development of visual devices, but it is not usually necessary in task execution.

The second category corresponds to the visual subsystems that are used to share information and coordinate activities between several stakeholders. These visual devices usually gather chunks of information from different sources, allowing data sets to be simultaneously analyzed. These are often used as boundary objects (i.e., for passing information between different departments or hierarchical levels in the company) and may be intended for several user groups (e.g., design managers, material supply staff, production managers). Some devices may summarize a large amount of information using graphs or tables, providing an opportunity for reflection. This is the case of the customization choice board (Fig. 6) or the visual planning and control board. This type of visual subsystem typically produces routine information (e.g., daily, weekly, monthly).

Finally, at the highest level of integration are visual devices intended to facilitate collaborative processes, such as planning and control, quality assessment, and accident-prevention meetings. These devices are highly dynamic. They can be used to support collaboration within a specific group of users or among different departments or hierarchical levels. They play an important role in environments in which flexibility and innovation are important. This is the case of Company G, considering that there was an explicit strategy of customizing their products. These VM subsystems may be connected to some key events carried out in a project, such as site layout planning, long-term production planning, and defining the sequence of tasks in communal areas (Fig. 7).

It is worth mentioning that some VM subsystems can be classified into different categories, depending on how they are used. For instance, the physical prototyping in Company G fits well in the third category (collaborative visual subsystems) because a meeting was held during prototyping to share experiences and to define improvement measures. This meeting typically involves the design team, representatives of the sales department, and production managers, and at the end all improvement opportunities are documented and displayed. In other companies, physical prototypes should be simply considered coordination visual subsystems because they do not support any type of collaboration (Saffaro et al. 2006).

Moreover, these three categories of VM subsystems do not represent a ranking in terms of importance. All of them are important for providing process transparency, but they have different and complementary roles. The idea of dynamic visual devices is also important for all of them.

Main Contributions

The main contributions of Stage 3 relate to prescriptions on how to devise and implement visual subsystems to support production management: (1) Company G has effectively used the idea of boundary objects to integrate the work of different departments (e.g., customization choice board), which may help to mitigate problems related to complexity by sharing timely information and removing information barriers; (2) this empirical study also provided some examples of visual devices that have been carefully designed with some degree of participation by the workforce, taking into account the mental models of the users (e.g., standardized worksheets, k*anban*); and (3) several visual devices have been used not only to create communication channels but also to support coordination and collaboration (e.g., constraint analysis board for communal areas, physical prototypes).

Proposed Model and Guidelines

The proposed model represents the main tasks involved in the development of visual management systems, including both visual and nonvisual work, as suggested by Nicolini (2007). It also contains a number of guiding questions that define the scope of decisions involved in each stage. An iceberg metaphor was chosen for the visual representation of the model (Fig. 10). Such a metaphor can facilitate the dissemination of the model among nonspecialists, which may be regarded as a contribution to the industry (Eppler 2003).

The model divides the conception of VM systems into four steps (Fig. 10). The fourth step is the only one that is visible, i.e., it involves visual work. Typical decisions involved in the design of a visual device must be considered, such as type of coding (e.g., color, shape, texture, symbols), information display format, and forms of dissemination. At this level, knowledge from the field of ergonomics, related to the design of operator interfaces, is very relevant (Tezel et al. 2016).

However, the inclusion of three other steps provides a comprehensive understanding of the process of conceiving VM systems. Indeed, Steps 1–3 may consist of a substantial part of the work involved in the conception of these systems.

The first step consists in analyzing the process, with the aim of identifying its main problems, its potential causes, and who is involved. Besides direct observation, other sources of evidence may also be used, such as analysis of documents and interviews. The second step involves an analysis of users' needs regarding what information is relevant and what should be the purpose of the tool, considering users' mental models. The third step is concerned with the integration of the visual device into the process or routine considered, considering whether it is necessary to perform coordination tasks and promote collaboration. This is particularly important in the case of dynamic visual devices.

Using the development of a *kanban* system for material supply (such as the one for dry-wall partitions from Company F) as a hypothetical example for the application of the model, these are the activities that are typically involved in each step:

1. Step 1: An analysis of the process should be made at this level, in which the main problems related to the supply of dry-wall components are investigated. If the improvement initiative is based on the lean production philosophy, waste (non-value-adding work) must be identified, such as material waste, delays, waiting time, and large inventories. Such an analysis should check whether there is a standard procedure for performing this task and how communication occurs between the crews in charge of installing dry-wall partitions and the material supply team. A key decision at this level is whether a high degree of process transparency and autonomy is suitable for the context of the company.
2. Step 2: This level involves an analysis of the needs of the visual device users (material supply and installation crews), considering the level of literacy and previous experience with the use of *kanban* systems, among other factors. It is important to identify what information is necessary for those users and when and where it should be accessed. If available, existing communication codes should be identified.
3. Step 3: This phase consists in defining the expected actions to be carried out from the use of *kanbans*, such as organizing kits, checking, moving materials, and taking corrective actions in case something goes wrong. Some key decisions involved at this level are the frequency of use and who will produce the information for the delivery of materials.
4. Step 4: This stage is concerned with the design of the *kanban*, including the type of coding to be used, the precise content of the information, where it should be displayed, and whether it is necessary to use some kind of warning.

Therefore, from a practical perspective, the model prescribes that there should be a balance between the tasks involved in those four steps. It indicates that the development of a visual subsystem is much broader than simply designing a visual device. Rather, it is necessary to understand existing problems, identify user needs, understand how the visual device is going to be integrated into the process, and, finally, design the visual device.

An important contribution of this model is that it connects key concepts related to VM that have been proposed in different fields of knowledge. The visual thinking concept (Mange et al. 2015) guided the construction of the model. The concept of visual literacy, suggested by Avgerinou and Ericson (1997), and the visualization risks pointed out by Bresciani and Eppler (2008) were considered during the definition of the model steps.

The model is also useful for separating the roles of the different taxonomies proposed for visual management. For instance, the taxonomy of the visual management functions (Tezel et al. 2016) can be used in the second step of the model when identifying the aim of a visual device. The taxonomy proposed in this investigation for the degree of integration of visual devices in managerial process is critical for the third step of the model. The taxonomies concerned with the type of visual device, such as the level of control (Galsworth 1997) and whether it is static or dynamic (Eppler and Pfister 2011), can be used in the fourth step. Overall, the connections between the different types of existing taxonomies can improve our understanding on the underlying ideas of visual management.

Based on the literature review and on the empirical studies, a set of guidelines for designing and implementing visual management systems is proposed. These guidelines have clear connections to the four steps of the model, as presented in what follows:

1. Emphasize the role of visual devices as boundary objects: Visualization of some project information may be important not only for a specific group of people for task execution and control but for establishing a common understanding and supporting the exchange of information between different departments and hierarchical levels (Steps 1 and 2).
2. Consider the mental models of the users: Assumptions, beliefs, generalizations, illustrations, and previous experiences that influence the behavior and understanding of users should be considered in the design of visual management systems. This reduces the amount of information to be provided in visual devices, making them easier to interpret (Step 2).
3. Help to motivate people and support decentralization: A visual management system can change the way employees feel about their work, contributing to increased morale and motivation, by promoting collaboration, decentralizing decisions, and increasing the degree of autonomy among production teams (Step 2).

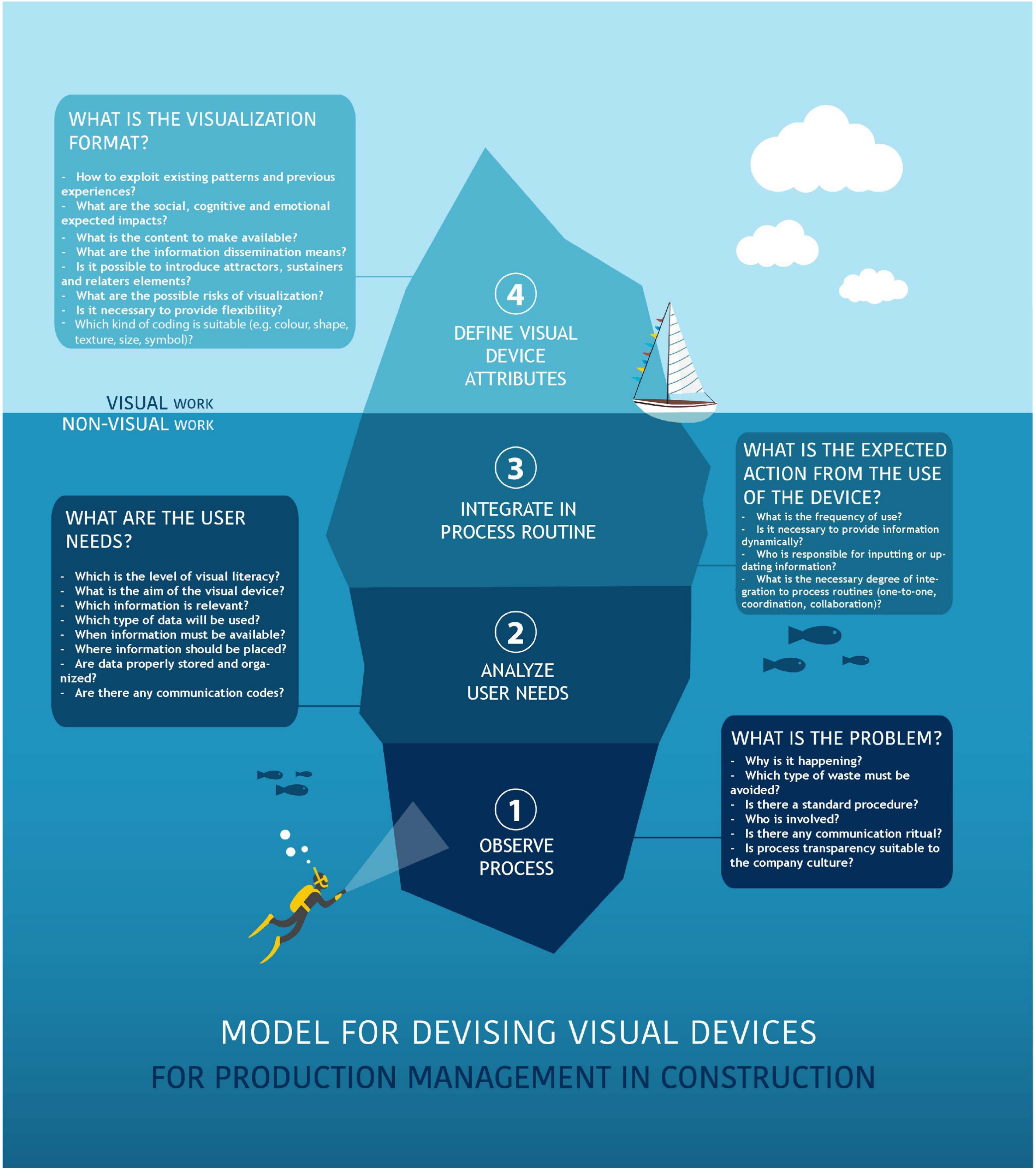

Fig. 10. Model for devising visual devices for production management in construction.

4. Provide timely information and quick feedback: A visual management system should provide timely information and quick feedback so that corrective actions can be taken on time (Step 3).
5. Support communication rituals in collaborative meetings: Visual devices should be associated with learning initiatives and moments of reflection. When a visual device plays this role, it becomes important to people and relevant to the process. Stopping in front of a performance board, even for a few minutes in a daily ritual, serves as strong evidence that this visual device is useful (Steps 3 and 4).
6. Encourage the joint processing of information: Some visual management subsystems should support collaborative activities

in organizations. These types of visual devices can be used as catalysts to facilitate a variety of tasks, from the generation of ideas to decision-making, planning, knowledge sharing, and learning (Eppler and Bresciani 2013) (Steps 3 and 4).

7. Mitigate problems related to system complexity: Some visual devices can provide support to deal with complexity by sharing the right information on time and removing information barriers in the work environment (Steps 1 and 4).

Conclusion and Suggestions for Further Work

The use of visual devices in operations management for performing different functions, such as control, coordination, and innovation, has been investigated in different fields of knowledge, including construction management. However, there are important knowledge gaps related to the lack of understanding of VM underlying ideas. This investigation has explored one of these gaps, the complementarity between visual and nonvisual work, which is required to conceive and operate VM systems.

The main contribution of this research study is the development of a model for designing visual devices, which is applicable to the context of production management in construction. This model is divided into four steps: (1) observe the process; (2) analyze user needs; (3) integrate visual devices into a process routine; and (4) define visual devices attributes. Each step is connected to a number of guiding questions that define the scope of the decisions involved. Some concepts proposed in other fields of knowledge, such as visual thinking, visual literacy, collaboration rituals, and boundary objects, were considered in the development of the model.

As secondary contributions, this investigation proposed a set of guidelines for designing, implementing, and assessing visual management systems, which are directly related to the steps of the model, and also a taxonomy of VM practices according to the degree of integration with managerial processes (one-to-one, coordination, and collaborative visual subsystems).

Regarding the limitations of this investigation, it must be pointed out that this research work is exploratory, at the level of solution incubation. Indeed, the model emerged in the research process and has not been tested in an organizational context. Also, the practices adopted by the companies involved in this investigation are highly related to the particular context of each particular empirical study, and the assessments that were carried out cannot be generalized for the whole construction industry. However, this paper points out some underlying ideas behind some advanced visual management practices that have been successfully implemented by companies within the construction industry and from other sectors and highlights some of the difficulties faced by those companies in implementing VM.

Another limitation of this research study is the fact VM systems were analyzed from a construction project perspective in both empirical Studies F and G. Instead, some of the VM practices (e.g., *kanban*) could be used to support managerial processes at the level of supply chains.

Finally, some opportunities for developing further research have been identified in this investigation: (1) evaluate and refine the proposed model and the set of guidelines for conceiving VM systems by fully or partially implementing them in organizational contexts; (2) explore the use of ICT-based visual devices in the development of the model; (3) investigate how social and cultural issues associated with users' mental models can be better explored in the implementation of VM in the construction industry; (4) devise VM approaches for enhancing innovation and stimulating creativity in continuous improvement efforts at construction sites; and (5) investigate how VM practices can be improved by considering visual perception and pattern recognition in the design of visual devices.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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