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Master's Dissertation **2017**

Identifying Factors to Improve Real-Time Collaboration in High-Rise Construction

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Major in System Design and Management

ABSTRACT

Student Identification Number	81534683	Name	Daum, Daniel

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Identifying Factors to Improve Real-Time Collaboration in High-Rise Construction

Abstract

Innovation with emphasis on information and communication technology (ICT) has become both a success factor and impairment in high rise building (HRB) construction projects worldwide. Construction is shifting from individual knowledge work to team-based collaboration but lags due to its size and complexity behind other industries in respect of both acquisition and use of mobile communication systems to improve collaboration of its workforce. According to interviews, the level of skilled construction workers is expected to increase by 10% or more in the next years and thus, identifying the potential of streamlining collaboration by construction personnel on sites will be vital to success in future projects.

This exploratory study investigates the perceptions of three construction stakeholders, namely construction workers, construction managers and technology providers, and identified forty-five (45) factors including four (4) key implementation strategies that support or constrain real-time collaboration in HRB projects. The paper aims at providing stakeholders a clearer understanding on the implication of coordinated actions, strategies and policies.

The study revealed forty five (45) factors to improve real-time collaboration in high-rise construction. Three countries have been observed and the differences between have been concluded. The study identifies that emerging mobile communication technology has the capability to not only improve data and information sharing but rather clearly confirms that it improves work performance entirely in practice. A collaborative system model has been developed by using Causal Loop analysis and Bayesian Network models to analyze systemic actions. The most suitable devices and interventions for each country have been concluded.

Keywords

ICT, mobile communication, real-time collaboration, high-rise building construction

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To my friends in Keio SDM, I am proud to have made this program together with them. Students at Keio SDM are probably one of the most underrated professionals out there, and I want to say thank you. I grew personally with every single talk to all these bright and impressive personalities. It was a great honor for me to get to know them all.

Lastly, this work was supported by several experts and without their goodwill and commitment no model of comparable quality could have been developed with the limited time. These individuals, thus, deserve the highest credit for their supervision and collaboration.

1. INTRODUCTION

In recent years the construction sector plays a vital role in society, accounting for 6% of the global GDP [1] and will become even more important in future because of several global mega trends such as migration into urban areas. Especially the construction of high-rise buildings (HRB) has an ever increasingly complex nature and is entirely reliant upon efficient communication between individuals and considered one of the most information-dependent industries [2]. Indeed, the sheer number of construction workers involved in the processes undertaken during the construction renders the communication networks on sites exponentially complex. But, HRB construction is and has ever been by virtue of its harsh and dangerous conditions a follower not a technology leader [3]. It has been hesitant to embrace latest innovation opportunities and in contrast to other industries, its productivity has stagnated over decades. This development can be attributed to several challenges: the persistent fragmentation and information dependency; poor collaboration between construction workers involved in the project; the industry's difficulty in acquiring and using new information and communication technology (ICT); and constraints in recruiting and training a talented and future-ready workforce. The amount of information generated and exchanged during the construction process is substantial and the distance between construction company headquarters or even the site offices with the actual construction sites augments significant communication problems. On one hand, the emergence of efficient ICT systems in recent years massively boosted the speed of information flow and reduced the cost of information transfer for construction site offices. On the other side, construction projects take place on construction sites where personnel have difficulty in gaining access to required information.

Construction - by nature a team-based activity - requires its workforce collaborating, combining skills and expertise and these, in turn, demand new levels of communication between the people involved. Thus, although communication in construction led to improvements in project performance, this paper argues that construction is lacking behind other industries in its acquisition and use of ICT for effective collaboration in HRB construction. Emerging mobile communication solutions have motivated numerous construction organisations to invest and adopt in promising technology. Furthermore, the paper has found that wireless mobile computing systems have the potential to improve the information flow on construction sites but have not been exploited by today. In other words, a thorough implementation into the site environment has failed. Therefore, it is essential to understand the context of cultural, technological and social factors in ICT implementation on building sites and observe the real behavior, desires and the actual needs of field workers. The advantages of mobile computing solutions have been identified as essential for not only improving instant information flow by executives and management but also on the lowest level of the corporate pyramid, the workforce.

This study demonstrates how systems thinking and design thinking can be used to deal with the complex issues of collaboration in construction. Pairing technological with social aspects a systemic framework was developed, that may enable stakeholders in HRB projects to benefit from having a clearer understanding. Hence, the purpose of this paper is to understand the factors that support or constrain collaboration of craftsmen in high-rise construction projects [2]. A major driver for this development is that the construction industry lags due to its size and complexity behind other industries in respect of both acquisition and use of mobile communication systems. Not only time and cost, but quality control, in particular, getting accurate documentation of events, progress and conditions, need to be thoroughly optimised to reduce time delays and general downtime [4]. The objective of the construction industry, as of any other manufacturing industry, is to produce its products to satisfy its customers [5]. Time is of the essence. However, different is that the construction of a building is unique. When searching for how to increase construction productivity one can take a look in the manufacturing industry. With Industry 4.0 manufacturing processes are said to increase revolutionary within the next decade [6]. But, other than in manufacturing the construction industry remains year by year the same: Buildings take time. Can manufacturing be considered as a valid model for the development, design and production of a building? It can not. A building is a project not a product. Therefore, it is less productivity that needs to be improved but rather the rate of failures and quality. HRB projects are not only information-intensive but also involving a great number of people collaborating; nevertheless, the construction industry is and has ever been by virtue of its harsh conditions a follower not a technology leader. Despite an explosive growth in internet use in the last decade among all industries, construction has not kept pace to the same degree.

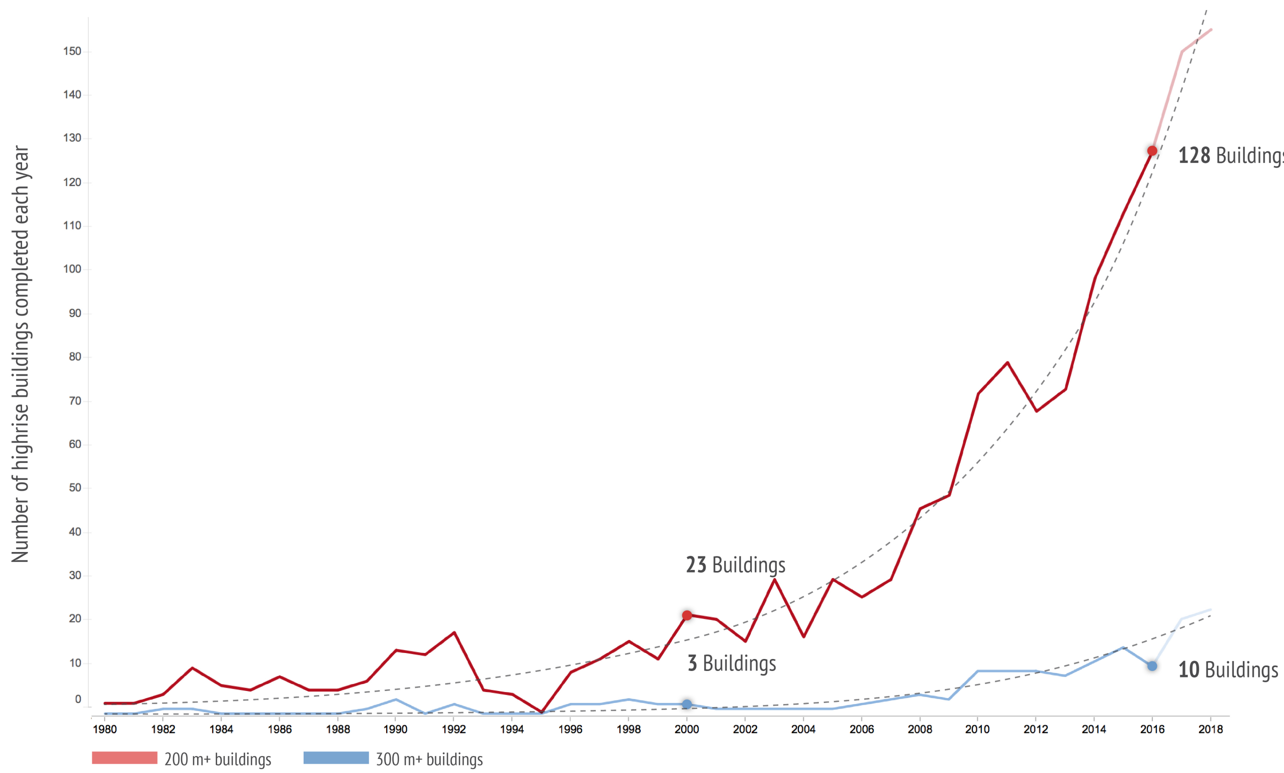


Fig. 1.1. # of buildings completed in 1980 - 2017. (Buildings 200+ Buildings 300+)
Source: The Council on tall Buildings and Urban Habitat

1.1. Growth of size and complexity

High rise buildings are becoming taller and being built faster, driven by rapid growth in Asia and the Middle East. The number of super-tall buildings, that means 300 meter plus, in the world has tripled in the last seven years. Also the total number of buildings over 200 meter in the world has seen a 441% increase from the year 2000 [7]. Figure 1.1 shows the global skyscraper surge in 2016 and indicates the projects until 2018. It must be pointed out that 107 out of 128 completed buildings in 2016 were constructed in Asia (see fig. 1.2) which represents 84% of the total projects and Asia, therefore, retained its status as the world's skyscraper epicenter. Building structures are becoming taller and being built faster, driven by rapid growth in Asia and the Middle East. The number of super-tall buildings, that means 300 meter plus, in the world has tripled in the last seven years. Also the total number of buildings over 200 meter in the world has seen a 441% increase from the year 2000 [7]. Figure 1.1 shows the global skyscraper surge in 2016 and indicates the projects until 2018. It must be pointed out that 107 out of 128 completed buildings in 2016 were constructed in Asia (see fig. 1.2) which represents

84% of the total projects and Asia, therefore, retained its status as the world's skyscraper epicenter.

In particular, even more sensational, 66% of the global 2016 total can be attributed to China alone. This was the ninth year in a row that China achieved this distinction. And, with over 300 high-rise buildings currently under construction [7], it is plausible to assume that the county's momentum will continue in the near future. Why the research focuses on high-rise construction projects rather than general large-size construction projects has to do with its nature. With the exponentially increasing complexity of building structures and techniques also requirements of skilled trade workers as well as their communication grow. BC projects are not only highly information dependent, but involving a great number of people collaborating to produce complex, one-off projects.

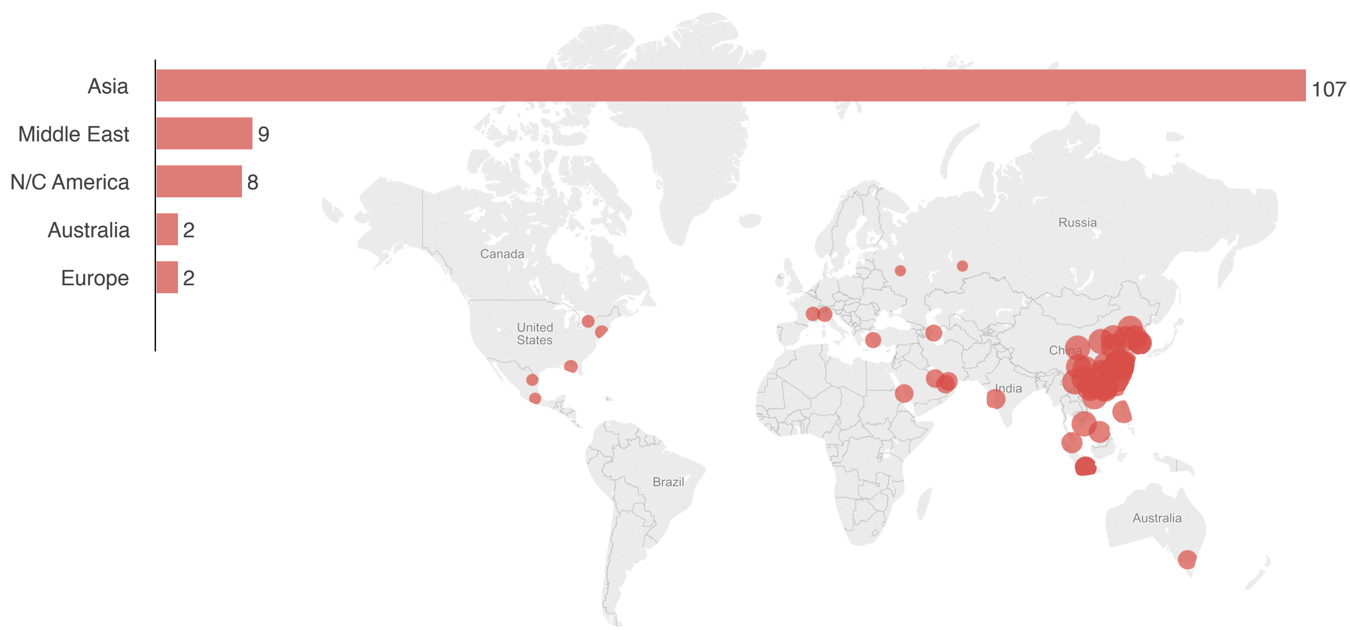


Fig. 1.2. # of buildings +200 completed in 2016 by region. Source: The Council on tall Buildings and Urban Habitat

1.2. Differences of high-rise constructions and conventional large-scale constructions

Major difficulties faced and presented to constructing high-rise buildings that commercial constructions do not face vary with scope and location but is mostly related to the enormous volume and vertical building direction as described in section 1.1. Usually high-rise buildings have construction phases of several years and be built in a high dense areas where pedestrians on the ground need to be protected from falling items and where street traffic must not be disturbed from the supply of materials and erection of scaffolding and cranes [8]. The scheduling of material delivery must be precise to the day and the hour in the critical path, and interfaces between hundreds of companies involved well coordinated. Additional, buildings sway on top floors due to wind loading and seismic loading. To give an example on the forces of wind on building structures: The balcony doors on the upper floors of Burj khalifa in Dubai were designed to lock themselves if the wind is strong enough to blow inhabitants off the building.

The study identified and categorised the major differences between high-rise building constructions and commercial large-scale constructions as seen in Table 1:

Specific items	**High-rise building construction**	**Conventional building construction**
Scheduling process	Critical path schedule	Progress schedule
Location	High density area	Low density area
Environment	High to extremely high wind loads	No particular problems
Transportation	Vertical transportation of goods and personnel only via provisional elevators	Mostly at ground level and sufficient
Safety measures	High-altitude safety measures; Protection from falling items required	General safety levels
Safety (Fire)	Construction personnel cannot leave quickly	Construction personnel can leave quickly
Practicalities	Construction goods and personnel need long travel times to and from the upper levels	Construction goods and personnel need moderate time to reach levels
Personnel	Highly specialised professionals required (Lack of qualified professionals) Narrow selection of construction companies	Medium to high-skills required

Table 1. Differences of high-rise constructions and conventional large-scale constructions

1.3. The value of knowledge as organisational asset

Knowledge and expertise, possessed by construction's workforce, is a vital resource that contributes to a very considerable extent to organisational success and project quality. The process, by which knowledge is created or acquired, communicated, applied and utilised must be effectively coordinated. Architects; general contractors; structural, civil, mechanical and electrical engineers; subcontractors; tradesmen; project managers; laborers; building suppliers; and other practitioners are involved in the daily exchange of information. But surely we first must start by defining the meaning of the word "knowledge". It is important to understand what constitutes knowledge and what is the difference of two other concepts, namely data and information. To visualise: Data can be seen as the lowest item, an unstructured collection of facts and figures. Information is the next level and regarded as processed and/or structured form of data. Information thus paints a bigger picture; It is data with relevance and purpose. Knowledge is defined as “information about information” [9]. The knowledge, possessed by each individual, is a product of his experience and an ability to turn information and data into effective action [10]. We think of knowledge as something that can be recorded in words, visualised or taught. But, this is not always the case. Now that we have drawn boundaries between knowledge, information, and data we can go one step further and look at the forms in which knowledge exists and the different ways that it can be accessed and shared. The different forms of knowledge relevant in BC projects can be grouped into two categories: Explicit knowledge and tacit knowledge. The former refers to codified knowledge, such as that found in documents and software, while the latter refers to non-codified and often personal and experience-based knowledge. Some researcher make a further distinction and talk of embedded knowledge. This way, one differentiates between knowledge embodied in people and that embodied in processes and organisational culture, but this won’t be of germane to the present discussion. Explicit knowledge is articulated, expressed and recorded as words, numbers and codes [11]. This type of knowledge is formalised and codified and is often referred to as “know-what”, “know-why” and “know-who”. It is therefore fairly easy to identify, store and retrieve. This is the type of knowledge most easily handled by knowledge management and IT applications but only represents a minor part of 5%. From a managerial perspective, the greatest challenge with explicit knowledge is similar to information: It involves that people have access to what they need.

95% of applied knowledge on the other hand refers to the second form of knowledge: Tacit knowledge stands for “know-how” and indicates intuitive, hard to define knowledge that is largely experience-based. Because of this, tacit knowledge is often context dependent and personal in nature. It is hard to communicate and deeply rooted in action, commitment, and involvement and thus a challenge for IT. Firms would like to prevent knowledge loss due to employee turnover. However, tacit knowledge almost always goes with the employee. It is also regarded as being the most valuable source of knowledge and the most likely to lead to breakthroughs in the organisation [12]. J. Wellman argues that the exact extent to which IT systems can aid in the transfer of tacit knowledge is rather difficult to define. Current solutions struggle to convey our intuitive understanding gathered from years of experience and practice. Virtually all practitioners rely on this type of knowledge, hence it is rather tacit than explicit knowledge which will be of value for the evaluation of ICT implementation.

The implication of the above mentioned discourse is that information technology in BC projects, that focuses on creating information access out of only explicit knowledge is and will be namable limited in terms of its contribution to enhance project quality. A thorough identification and understanding of the both types of knowledge available to projects' executions is the first step in understanding how to manage them. The view of knowledge as an asset to be guarded sees humans as capital [11] and consequential the role of ICT in this relation must be that of an important enabler, merging people, processes and knowledge. IT has contributed in the previous two decades to enhance the pace of processing data but in recent years, however, information communication technology (ICT) whose definition is rather the utilisation of digital technology to communicate and coordinate the two forms of knowledge draws attention by the industry in regard to achieving innovation. In recent years construction is shifting from individual knowledge work to team-based collaboration and *much more* communication and coordination will be needed to fill the usage-gap of the field labor.

1.4. Communication need in HRB projects

It is important to recognise the term communication to be multi-facetted and complex in itself, having different meanings in different contexts. Despite the difficulties inherent in describing what is meant by ”communication” this section defines its concept relevant for collaboration on HRB sites: To communicate means in this study 'to bridge a distance between individuals or groups' from short and simple to long and complex. In construction these distances necessitate communication within a high-noice environment. Construction may be seen as a social activity in which communication plays a vital role [1]. If seen as this, communication activities can include engaging in conversations, listening to colleagues, networking, collecting information, directing subordinates, writing letters or transferring information through electronic devices such as cellular phones or computers. The latter was found to be the best suitable tool to improve voice-based communication. But, management practices have so far done little to engender an open communication environment that ensures conjoined collaboration and improved performance via the use of ICT.

The study found that current approaches to understanding and dealing with the complexities of communication in construction projects are non-systematic and mostly used in the head office and site office rather than on the building site, where face-to-face is still the main channel to communicate and paper with imposing 79 percent still the major medium to share information between trade workers on building site [3]. This paper argues that implementation of mobile communication systems into site environment has failed by today and lacks of systemic strategies. Hence, re-education and training for construction professionals will be necessary to promote wide acceptance of technology which leads us to the next chapter.

1.5. Construction information problem

Before embarking on identified problems, it is worth-while to discuss briefly the nature of construction information. Since the boundaries between knowledge, information, and data have been drawn before, and knowledge in particular has extensively been discussed, it is possible to go one step further and look at the forms in which information exists and the different ways that it is shared in BC projects. Construction information can be grouped into three categories: Domain information, organisation-specific information, and project-specific information. The domain information is, in principle, available to all companies and is partly stored in electronic databases. Organisation-specific information categorises all information available to a specific organisation such as standardised solutions to design problems, often used as reference cases within the organisation. It is company-specific and is the intellectual capital of the firm. The project-specific information category is tie to one specific construction project, but shared by several organisations that make up the supply chain. This category embodies the potential for usable knowledge to share among project practitioners [13]. It is both knowledge each contractor has about the project and the knowledge that is created by the interaction between several contractors within a project.

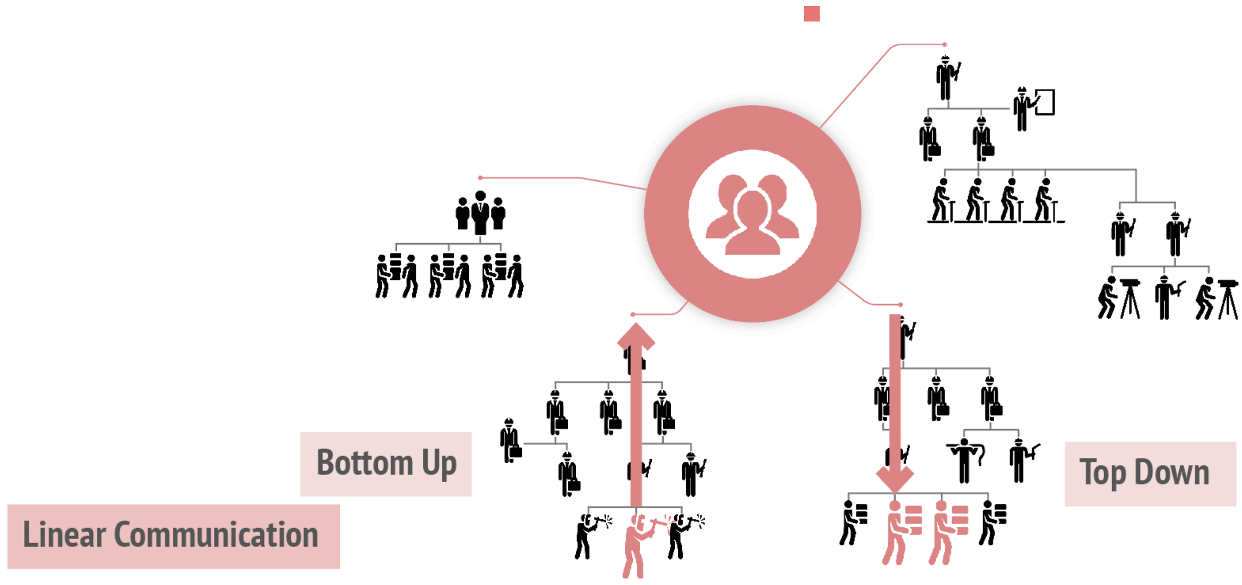


Fig. 2.1. Actual linear communication paths in construction. (Actual communication path)
Source: Tai S., Y. Wang and C.J. Anumba 2009

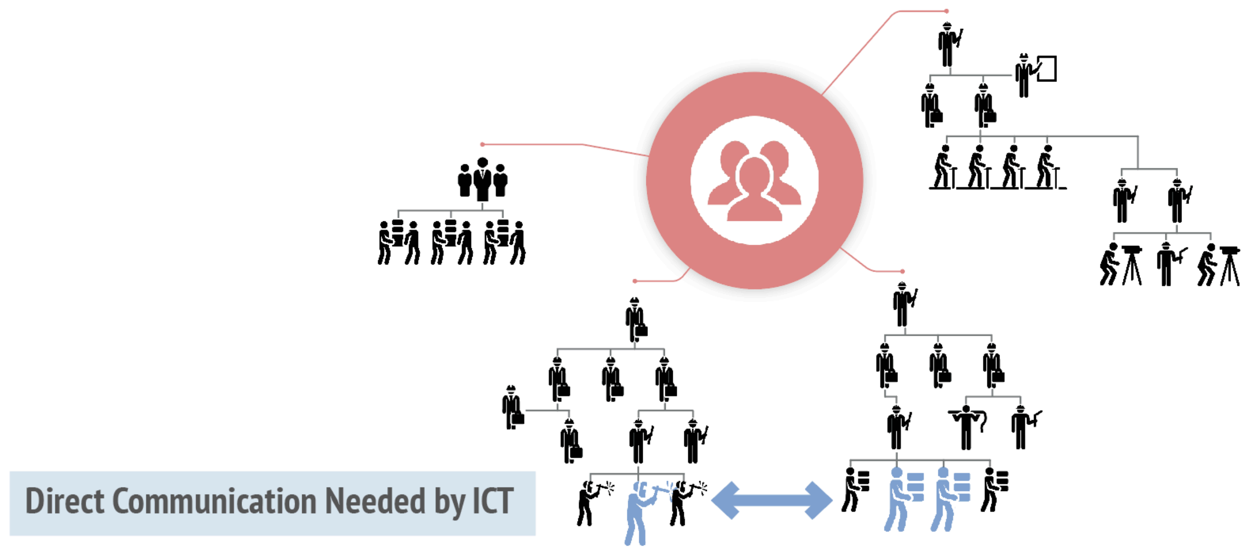


Fig. 2.2. Direct communication paths in construction. (Shortest communication path)
Source: Tai S., Y. Wang and C.J. Anumba 2009

According to Dawood and Hobbs [5], over thirty percent of construction problems are caused by inadequate coordination and inefficient means of communication of project information and data. Up to 12.4% of construction cost is wasted due to rework of failures detected late in the construction phase [14]. In a nutshell, lacking cooperation and communication between specialty trade workers, field management and project management as well as the lack of prompt decision makings on building sites need to be optimised. The purpose of this study is to generate a clearer understanding of both the effects and opportunities of utilising IT-based communication tools on sites. To design and communicate a proposal with sufficient clarity and to gain industry-wide acceptance not only the technical but rather human impacts will be of essence to identify the benefits and barriers of IT-enhanced communication in construction. The politics of knowledge sharing is an issue in nearly all industries. Especially the information dependent construction sector needs a supportive organisational structure to share and store knowledge. Intellectual capital, the brain power of organisations' workforce will be the true asset that needs the interest of IT. Information technology and particularly ICT should be less exploited to store and share information but rather in its potential to aid cooperation, collaboration and overall communication between people.

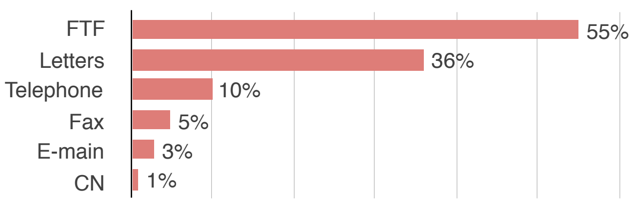


Fig. 3.1. Communication channels in large-scale BC projects. (FTF: Face-to-face; CN: Computer Network)

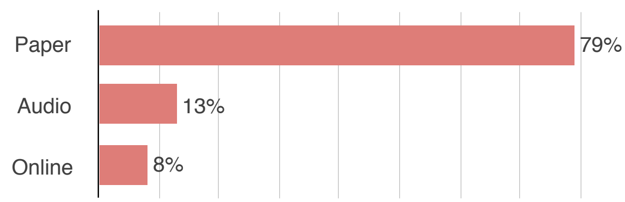


Fig. 3.2. Communication medium in large-scale BC projects.

Previous research has shown that current approaches to understanding and dealing with the complexities of ICT in BC projects are non-systemic and mostly used in head offices and site offices rather than on building sites [15], where face-to-face is still the main channel to communicate (see fig. 3.1) [3] and paper with imposing 79 percent still the major medium to share information between trade workers on building site (see fig. 3.2). The development of appropriate technologies for the use on sites should - similar to the use in site offices - ensure that Return of Investment (ROI) exceeds the cost of obtaining the information wirelessly. For the sake of discussion, this paper argues that implementation of ICT-based communication systems into site environment has failed and lacks a systematic strategy. Therefore, thorough re-education and training for construction professionals will be necessary to promote wide acceptance of technology which leads us to the next chapter.

1.5.1. Global construction labor shortage

A major paradox in construction around the world is a skill and manpower shortage as building projects boom, in which a downturn has led to a situation in which many specialty trade workers and professionals have switched industries. Contractors face problems in hiring workers with profound experience. On the other side, the major contribution to the industry by more then 40% is provided by the age group 45 +, which is the next group to face retirement [17].

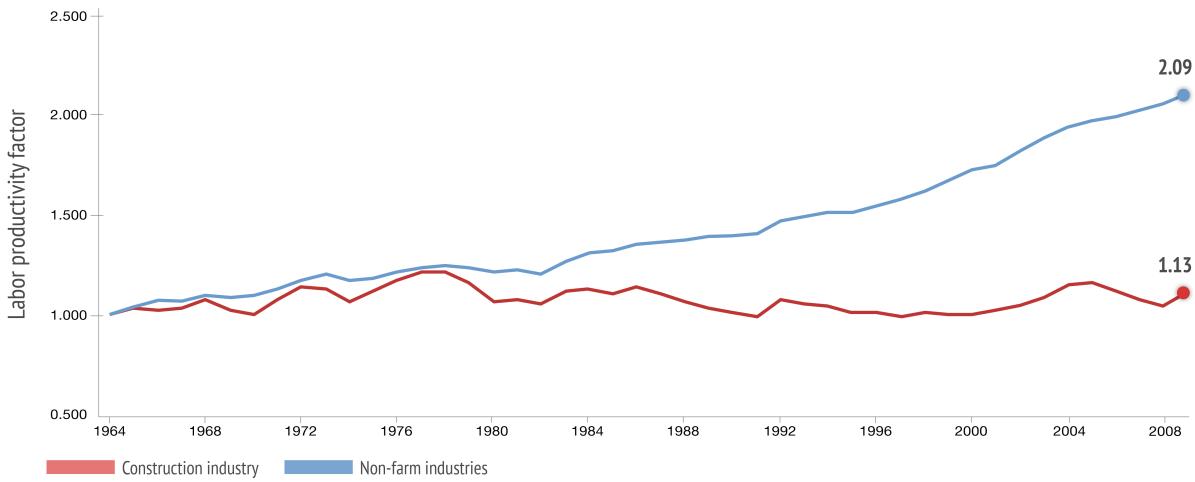


Fig. 4. Labor productivity in large-scale BC projects. Source: Eastman C. BIM handbook 2011

With an existing existing skill shortage in certain supervisory roles and skilled craftsmen, construction can do nothing than attract and sustain labor to not fully run out of balance. Job growth and replacing older workers will require grace for workers which could be created by a human-centred re-design of workers' roles in future projects. Fig. 3 indicated an exponentially increasing gap between construction and the non-farm industries in the labor productivity of skilled field personnel, starting in the early 80s when information technology has emerged. To catch up with other industries in the use of mobile communication systems, not only the management level but all involved professionals in HRB projects have to go into *higher gear*. Technology trainings and re-education should be measures to attract youths into the construction sector. Because, when teams collaborate and work effectively, this can lead to group accountability and mutual responsibility for achieving results. This forms the basis of 'high performance' team environments. Hence, effective communication is a key enabler of high-performance team working, in that high performance teams thrive in open communication climates, where ideas and information are freely exchanged in a collaborative workplace environment. Used correctly, ICT may have the potential to redefine the ways in which the industry operates [17].

1.6. Innovation efforts in construction

Can Construction's problems be solved by technology? Which technology, if so? As we will point out in section 2.1, the trend in construction indicates an increase of self-performed work and therefore a shift in resource management. In other words, general contractors (GC) change their focus from hiring specialty trade contractors to perform the work towards self-performing most of it. The complexity of managing the schedule of multiple separate companies on the labor side is significantly more difficult than managing all labor under one roof. This is primarily due to the fact that each sub-contractor is focused on its own profitability as opposed to the profitability of the group.

The progress of disruptive technologies such as Artificial Intelligence, Internet of Things, or Knowledge Warehousing creates solutions that blur the boundaries between physical and digital world. As a natural result, contractors must manage the increased transfer of data in their projects, which has limited one of construction's most important driver for success: Collaboration. An organisation thrives not only from the technology skills and knowledge of younger employees but also from the prudence and know-how of the older members of their personnel. Technology companies must have a granular understanding and further identify not only functional but rather emotional needs construction personnel to design solutions that meet their expectations. Data sharing is knowingly simple to achieve and more or less on its way in construction's every day projects. However, talking of enhancing collaboration we can analyse why organisations struggle with venturesome steps in technology adoption. According to a method from IDEO (Table 1), we can evaluate the innovation efforts within an organisation in three categories namely incremental innovation, evolutionary innovation, and revolutionary innovation [18]. By mapping innovation efforts along a vertical axis representing existing to new offerings and a horizontal axis representing existing to new users, we can get a clearer picture on the efforts for implementing latest technologies.

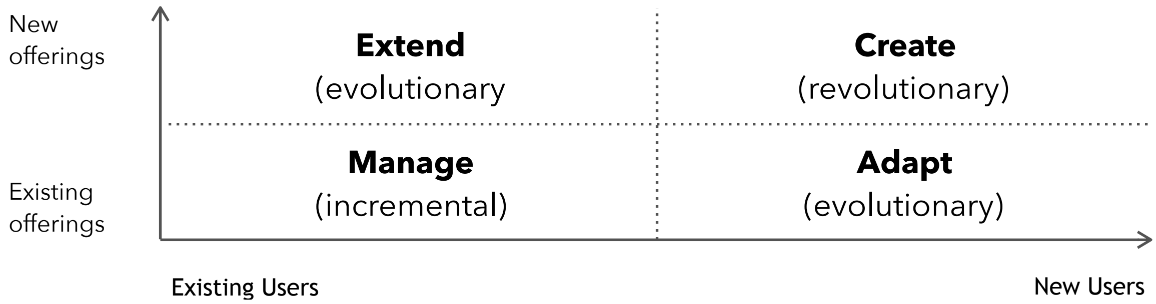


Table 1.1 Innovation efforts within an Organisation ("Ways to grow" matrix by IDEO)

Technologies located in the bottom-left corner close to "Existing offerings" and "Existing users" are incremental in nature. The majority of companies' effort is likely to be put in this type of innovation. Both the users and the product remain the same and companies secure theirs base. However, evolutionary technologies stretch the base into new directions: Innovation efforts are spent by either extending existing offerings to satisfy current users or adapting them to satisfy new users or new areas. Evolutionary innovation along the user axis might involve adapting an existing product so that it can be manufactured at lower cost and thus marketed to a wider user segment. The most challenging type of innovation is that in which both the product and the user are new. Revolutionary innovation creates entirely new markets, but happens only rarely. Sony achieved this with its Walkman and Apple twenty years later with its successor, the iPod. In neither case was the core technology new but both companies succeeded in creating a new market for a new form of experience. In the construction industry, the laptop pc and later the tablet pc were evolutionary since both created new experiences for their current users. Architects, Managers, and Engineers could open all their data nearly everywhere and to all time on building sites.

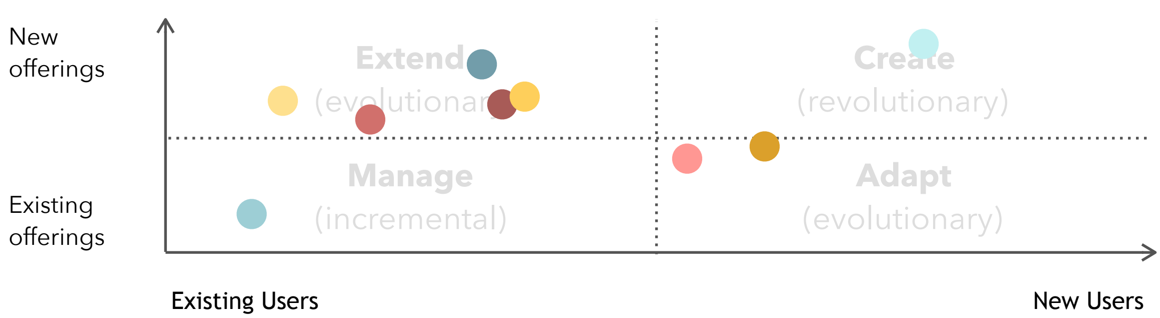


Table 1.2 Innovation efforts within an Organisation ("Ways to grow" matrix by IDEO) with available technology

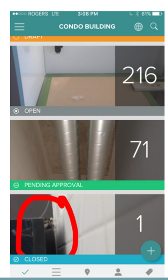
		
In-ear bluetooth headset	Integrated headset	Wearable camera
		
Laptop PC	Tablet PC	Cellular Phone / Smartphone / PDA
		
Two-way Radio	Software Applications	Smart Hard Hat

Table 1.3 Technology used for communication in construction (Images used for illustration purposes only)

As seen on table 1.2 the study evaluates the innovation efforts spend in the last twenty years on a multitude of mobile computing and communications solutions including smartphones, tablets, handheld devices, and two-way radios implemented with the aim at contributing to streamline information sharing and communication among the workforce on high-rise building sites. Advances of mobile computing and communications solutions are enabling organisations to exceed benchmarks in effectivity, collaboration, and decision-making. According to a survey by VDC Research of 816 IT decision makers in 2014 [19], the annual mobile budgets to support the mobility of workers was expected to grow by 10,3% over 2013. Construction firms have long known the advantages of working with mobile communication solutions. With today's increasing size of construction project and distributed and mobile workforce, there is a great need to connect these practitioners with appropriate and cost efficient tools. The study identified the common forms of technology used on building sites (table 1.3) and compares advantages and disadvantages of the two most applied tools for voice-based communication (table 1.5).

Tool	Purpose	Reception / Coverage	Audio Quality	Network Access	Availability	Physical performance
In-ear bluetooth headset	Enabler	-	Moderate	-	High	High
Integr. bluetooth headset	Enabler	-	High	-	High	High
Wearable camera	Enabler	-	-	-	-	-
Two-way Radio	Voice-based communication	High	Moderate	High	High	High
Software Applications	Enabler	-	-	-	-	-
Smart Hard Hat	Data / Voice-b. communication	High	High	High	High	High
Laptop PC	Data / Voice-b. communication	Moderate	Poor	Moderate	Poor	Moderate
Tablet PC	Data / Voice-b. communication	Moderate	Poor	Moderate	Moderate	Moderate
Smartphone / PDA	Data / Voice-b. communication	Moderate	Poor	Moderate	High	Moderate

Table 1.4 Specification ICT tools

1.7. Definition effective mobile communication

In this research, mobile computing and communications solutions are classified into "reception / coverage, audio quality, network access, availability, and physical performance". The role of a two-way radio serves a very specific purpose as that it leverages a private network to provide immediate and reliable voice-based communication. Smartphones and tablets, conversely, represent multi-purpose devices that, while highly functional, cannot serve the required reliability needed to make decisions in the fragmented workflows. Recent developments support the value of two-way radios in the construction industry and in this section the study compares some of the specific advantages and disadvantages of two-way radios when compared with cellular systems (Table 1.5). Compared with cellular phones, two-way radios have a substantially lower total cost of ownership over smartphones, which have ongoing network service fees. Here it is worthwhile to discuss the distinction between privately owned smartphones and the ones provided by the organisation. In overall, two-way radios enjoy a great coverage on construction sites - e.g. in lifts or basements - and have therefore the ability to work in places where cellular phones do not and reduce worker downtime. Advances in two-way radio technology provides better reliability, utility, lower overall costs [20], and above all retain the characteristic of the tools to be manufactured extremely sturdy and durable and thus a convenient product for construction.

Two-Way Radio 	**Cellular Phone (Smartphone)** 
Ensures privacy via a closed network	Exposes callers via an open network
Increases efficiency with **one-to-many** communication	Decreases efficiency by limiting communication to either **one-to-one** or **one-to-two** people
Excellent reception (within range) and wide coverage	Prone to dead spots and poor reception
Works even in times of emergencies and natural disasters	Subject to outrages from call overload, power failures, and natural disasters
Effective in highly noisy environments	Ineffective in highly noisy environments
Ruggedly built for work environments	Too fragile for work environments
Low overall cost (Low or no monthly fee for usage)	Costs money every month (Hidden fees and surcharges)
No web-based features such as social networks, email, or data sharing	Full usability of web-based features such as social networks, email, or data sharing

Table 1.5 Advantages and Disadvantages of Two-way Radio versus Cellular

The listed key advantage of two-way radios “One-to-many communication” is in other words simplified conferencing. All users of a system can hear every broadcast when dialled into a particular channel, which makes coordinating group action much easier than having to call individual employees via smartphone. Today, the advent of smartphones leaves decision makers in construction with an ambiguous choice: Is cellular a better technology because of the rapid introduction of new features, or do the pros of two-way radio still outweigh the cons? According to a 2014 report by VDC Research on the benefits of two-way radio versus cellular [19], annual failure rates of cellular devices are a whopping 18-20% compared to the relatively small 4-8% of rugged two-way radios. The same report estimates a loss of between 60 to 120 minutes each time a device is damaged, highlighting the problem of downtime due to cellular device failure. Furthermore, emergencies often leave cell networks vulnerable to systemic overloads, making most cellular phones and tablets all but useless when they are needed the most [19]. This above described analysis on both the advantages and disadvantages of two-way radios and cellular phones grants the former as the top contender for building construction, where the reliability of voice-based communications is paramount. Overall, two-way radio is ultimately more cost-effective and easier to use than cellular, and keeps workers in-touch and productive even in instances where communications networks are unavailable.

1.8. Development of hypothesis

Emerging information and communication technology has motivated numerous construction organisations to invest and adopt in promising ICT systems. It has been found that wireless mobile computing systems have the potential to improve the information flow on construction sites but have not been exploited by today; in other words, a thorough implementation into the site environment has failed. Therefore it is essential to clearly identify the context of workplace, organisational and personal factors in ICT implementation on building sites and observe the real behaviour, desires and the actual needs of field workers. The advantages of mobile computing solutions have been identified as essential for not only improving information and communication flow by executives and management but also on the level of field labor. Changing the exploitation of storing and retrieving

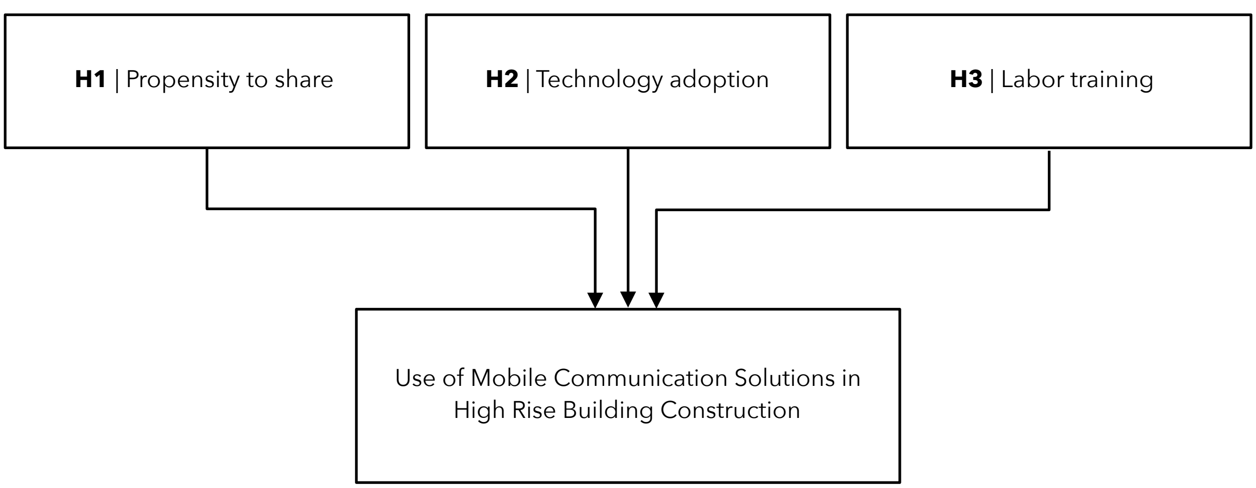


Fig. 5. Research hypothesis

information towards more voice-based collaboration in real-time between teams can counteract the stagnating efficiency-level in construction, that has been shown in the previous section. The variables and associated hypothesis are described below and are presented in figure 2.

The purpose of this paper is to understand the factors that support or constrain collaboration of craftsmen in high rise construction projects. The term collaboration describes a subsystem within the system "Construction" and is referred as the act in which two or more parties work jointly towards a common goal and is a key tenet for transferring 'know-how' among individuals in construction projects. To interchange the different forms of knowledge, factors such as organisational culture and policies, or personal propensity may influence individuals' attitudes about collaboration. The more the individuals believe that collaboration is correct, expected, and therefore supported workplace behavior, the more they should be willing to share their know-how. Hence, the study hypothesises that:

H1 | Propensity to share know-how is strongly associated with organisational culture and greater use of mobile communication solutions

A survey by FMI Corporation in U.S. found that the level of skilled trade workers is expected to increase in the next years [21] (See section 2) and one contributor to this large increase of requirements is that organisations expect to increase the amount of self-performed work in future. But, the more interdependent workers will perform their tasks, the more collaboration with others will be required. Not only the impacts, technologies have on individual performance but also social issues must be understood to improve collaboration on HRB construction sites. In other words, the willingness to collaborate should be higher when the technology attributes and conditions fall below the psychological cost of users (user-friendly solutions). As a result of this, the study hypothesis that:

H2 | Implementing mobile communication solutions at the level of individual craftsmen in HRB construction eliminates downtime caused by missing or ambiguous information

For collaborative technology to have positive impact on individual performance, workers should be motivated to use the technology . Even the best technology is of no use if people operating it do not function correctly. In other words, to implement technology on the level of individual craftsmen, the labor needs to be trained to be capable and comfortable with using it [22]. Hence, the study hypothesises that:

H3 | Labor training is strongly associated with the level of responsibility and task independence of workers

1.9. Objective of this study

The main objective of this study is to investigate individual perceptions of factors that underlie the acquisition and use of mobile communication solutions for collaboration in HRB construction. Furthermore, to develop a strategic decision-making framework that may guide organisations in the planning for effective collaborative working practices and the acquisition and use of suitable tools. The associated objectives are to: identify and define the needs and desires of construction site personnel; identify and define the perception of the three stakeholders, namely construction workers, construction management, and technology provider; develop an understanding of stakeholders' inter-dependencies and the role and responsibility of each in the entire system. This will provide stakeholders a clearer understanding on the implication of coordinated actions, strategies and policies to streamline mobile communication solutions on HRB construction sites.

1.10. Purpose and originality

Communication is a major problem on large-scale BC projects and as of today ICT systems have done little to promote collective teamwork on site. The internet in general helped moving information around but has done little either to bring project teams on site together. Effective collaboration systems, however, may not only reduce financial and knowledge losses but create more value to construction organisations and as consequence decisive competitive edge.

Even though the quality in BC projects has been improved in recent years as well as the amount of downtime has been reduced, most improvements have been achieved by maximising the access to relevant data and information. Nonetheless, it is possible to not only further improve project quality but achieve breakthroughs by enhancing team-based collaboration in real-time. The paper presents a new and collaborative, human-cantered approach to harness the power of teams to work on a wider range of complex problems. For construction it begins not elsewhere than at the root of organisations' brainpower: The workforce. In this paper, design thinking - as an approach that puts design much closer to the center of the enterprise is suggested. While past research works centred around specific team, project, or organisational levels, this paper illustrates a system perspective and takes human into the center. In particular, Design Thinking methods, inherently tentative and experimental, create a successful and fresh perspective into systems. Design has long grown out of its comfort zone in studios and emerges as a powerful tool for large technical and social problems. Creative and productive teams in construction projects need to be able to share their thoughts not only verbally but visually and physically to any time and thus new products are needed. However, to design and communicate the proposal with sufficient clarity and to gain industry-wide acceptance, the study pairs creative and rationale processes. In other words, systems thinking methods are paired with design thinking processes to present holistically systemic but human-centered output. The central focus, as presented in section II, lies on the collaboration and communication of data and information and particularly knowledge of construction's workforce. Thus, the outcome of this research will lead to clearer understanding of both the effects and opportunities on utilising IT-based communication tools on sites for construction management as well as technology providers.

Design thinking and systems thinking have no strong relationship. They are neither opposites nor do they have much in common. Both are not mutually exclusive but can be used together to solve problems. No study has been found applying one of the two methods within the context of construction projects. Design thinking is a process of synthesis, meaning it approaches problems by building things up from below. Systems thinking is most often associated with analysis. This is the process of breaking things down into their component parts in order to understand them.

	Systems Thinking	Design Thinking
Definition	The use of synthesis to create value and solve problems.	Thinking about strategy from an end-to-end perspective that considers broad implications.
Associated with	Synthesis	Analysis; Big-picture thinking
Differences	**The stakeholders are the designers**	**The design team observes and studies the stakeholders**

Table 2 Research Originality: Systems thinking and design thinking

The core differences in the systems thinking and design thinking approaches to problem resolutions are: Design thinking methodologies arose from the consideration of products and artifacts. The problems are ultimately resolved by people identified as designers by trade: The design team observes and studies the stakeholders. Systems thinking methodologies arose from the consideration of social systems: The stakeholders are the designers. System thinking cannot be a bottom-up operation nor can it be expert driven. It must actively involve the stakeholders of the design in shaping a shared vision that represents their ideas, perceptions, and values. The pairing of both top-down and bottom-up frameworks is it that makes this study original and of value.

Systems thinking and design thinking complement one another. Systems thinking is holistic following a method whereby the understanding of a system starts from the apparent issue and widens the system's boundary by expanding the circle to include those other factors that may not be apparent but have an influence or are connected to it. This way, the "whole" system and the relationships are identified prior to modeling the system and finding ways of improving the system to and moving towards a more desired outcome. Design thinking on the other hand, is more empathetic and human centered and requires the modeler to be inside the problem and design the solution after having walked in the shoes of the affected as opposed to being an expert who is invited to come in and help identify and improve on the problematic situation. This empathetic angle in design thinking will improve on the holism that Systems thinking emphasizes and seeks. It will give stakeholders a chance to walk in the shoes of others and increases their understanding of the problem and the potential to increase "innovativeness"/ innovation in the solutions arrived at. An increased understanding of the people in the system and the "whole" system itself is also to be gained.

Combining systems thinking and design thinking has the potential of improving on the holistic understanding of the current system as stakeholders have the opportunity to view the system from different angles. This has the potential to generate more informed ideas to transform the system with a more holistic view. An approach that combines the two should therefore be more holistic, empathetic and innovative.

Content	Originality
Observation	Conventional studies collected their data via either literature reviews or/ and interviews. This study conducted an extensive observation on several natures. A field observation and and field interviews in combination with literature review led to expert interviews and a questionnaire.
Design Thinking / Systems Thinking	Narrow versus wide: The paired development of synthesis and analysis in form of design thinking approaches and systems thinking approaches has not been applied by literature found in the context of construction.
Countries compared	U.S. and Germany as well as Japan were observed and a comparison was drawn. Identified factors have been shown and suggestions for each of the countries were presented. No literature has been found on the comparison between Western and Eastern countries in the context of construction and ICT.

Table 3 Research Originality

1.11. Personal motivation

The use of mobile and smart devices has in recent years steadily become a key part of remote communication on HRB sites with the result that today an increasing number of organizations are using mobile devices that improve real-time collaboration. Mobilisation enables companies to perform effectively and timely and avoid cost overruns due to unplanned downtime or failures. As it was described before, the nature of construction is challenging and dangerous, meaning one in five workplace fatalities occurring in construction drawing the highest accident rate of all industries [citation]. Although much literature has identified communication as the major determinant to reduce failure, there is not much initiative by large construction companies to equip their workers with available devices. Rather, companies remain in a ‘wait-and-see’ mode.

Working over ten years in construction, I developed an understanding of communication mechanisms and strived ever since to innovate the increasing prevalence of a mobile workforce. Laptop, smartphone, and tablet is already commonplace in the higher management levels, setting up the foundation for a paradigm shift away from the office-bound PC towards enhanced mobile workforce. But, workers take currently only a minor role in the integration of mobile communication devices. Within my studies as a product designer I developed a product that pairs active and passive safety measures and a low-cost communication platform that can provide real-time collaboration as it is embodied within a device that is part of every worker's gear: The hard hat. Interviews with construction professionals were conducted face-to-face and the feasibility of the product was evaluated.

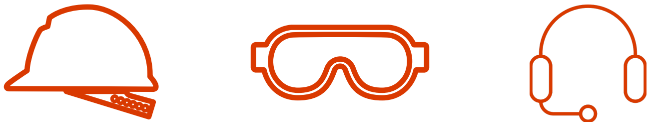


Image 1.1 Integrated headset to enable hands-free and remote communication

As a master's candidate in Keio's System Design and Management, I now studied the issue in its entirety to develop an understanding on the factors that support or constrain the success of such product integrations in HRB projects. And, the best route to accomplish this would be through the minds of industry and domain experts who had vantage points from the entire construction industry, rather than only my viewpoint. Products, as seen in this paragraph, could allow the use of the smartphone without the negative effects introduced before. I strongly believe, it's now about how smart devices can enable people to connect with each other remotely and instantly to create intelligent sub-systems that dynamically respond and collaborate. Collaboration and communication are paramount in mitigating delays and reduce the risk of them to be occurring to any time on site. To the favor of construction, technology today is available and affordable.

Image 1.2. Hard hat including headset and camera, designed by Daniel Daum

1.12. Structure of paper

The study collected and analyzed both qualitative and quantitative data in a sequential manner. It was divided into four phases as discussed below:

The first phase included interpretive analysis of the current communication mechanisms in construction and the benefits of effective ICT adoption as well as the nature of communication in general, conducted by literature reviews (quantitative and qualitative analysis). Aspects contributing to effective collaboration in construction and especially missing aspects were identified. The analysis led to the formulation of several hypotheses and identification of the best suitable research methods.

The second phase included conducting field surveys (qualitative analysis) in the German and Japanese Construction Industry to examine the current means of communication and mobile communication technology used to build the hypotheses in the research and to identify the factors that require further study. The field studies were undertaken on four large-scale construction sites. Two of them were located in the metropolitan area of Tokyo, Japan, one in the area of Stuttgart, Germany, one in Schaan, Liechtenstein. The interviewees have been in roles of senior management, project management, IT management, or had the authority of decision making in ICT implementation in construction companies and technology companies providing hardware and software relevant to the field. Constraints of construction professionals were observed and evaluated and valuable insights were gathered. A design thinking framework was used for the identification of users' functional and emotional needs and desires observing the real behavior of construction professionals in their natural environment.

The third phase comprised the study's main mode of data collection, a semi-structured interview survey (quantitative and qualitative analysis) by twelve interviews with domain experts involved in HRB construction. The interviews were conducted in Germany, Japan and the United States. Investigated were the experts' individual perception of factors that underlie the acquisition and use of mobile communication solutions for collaboration in HRB construction. Data analysis of the causal relationships between the identified factors led to the development of a systems thinking framework in general, and its second stage, the development of a holistic causal loop diagram in in particular. Furthermore, the data collected was used to test and further improve the hypotheses formulated in the research.

The fourth phase included a questionnaire study (quantitative analysis) that was developed in order to validate the factors identified in interviews and the data collected was used for populating Bayesian Network models. It included the topics of voice-based communication, the access ti information on construction sites, and the level of satisfaction with current mechanisms. Factors that constrain the use of mobile communication devices, trends in the industry and suggested actions to overcome and improve these identified factors were identified and evaluated.

The purpose of this four-phase, sequential observation was gain the understanding of stakeholders at the level of industry, organization, and - at forefront - from the bottom of the corporate pyramid, the workforce. Table 1 shows the relation between the four phases of data collection and analysis.

Research stage	Research Method	Research Objective	Applied Processes
1	• Literature reviews	• Study the current communication mechanisms • Find aspects missing in conventional studies that bridge the gap between the theory of communication and how it is practiced within the industry	• A survey of seventy-two (72) existing studies centred around collaborative working, current available tech-nologies, and several associated topics was conducted • Forty-five (45) factors that support or constrain collaboration were identified
2	• Field Observations	• Understand intuitive communication patterns, as well as the real behavior of construction professionals in their natural environment • Identify the needs and desires of buyers and users as well as the latest technology trends by suppliers	• Field studies on three (3)construction sites were undertaken and constraints of construction professionals were observed and evaluated • Design thinking was used for the identification of users' functional and emotional needs and desires • Meaningful insights were gathered
3	• Interviews	• Investigate individual perceptions of factors that underlie the acquisition and use of mobile communication solutions for collaboration in HRB construction	• Twelve (12) interviews with domain experts with domain experts involved in construction were conducted as main mode of data collection
4	• System model • Probabilistic graphical models (Bayesian Probabilities)	• Develop an understanding of stakeholders' inter-dependencies and the role and responsibility of each in the entire system • Develop a strategic decision-making framework that may guide organisations in the planning for effective collaborative working practices and the acquisition and use of suitable tools	• A questionnaire was developed in order to validate the factors identified in interviews and the data collected was used for systemic models • Focus group experts collaborated to establish a Bayesian Network model, using the Causal Loop analysis model to develop an understanding of stakeholders' interdependencies and the role and responsibility of each in the entire system • A comprehensive framework for systemic interventions was designed using probabilistic graphical models (Bayesian Probabilities)

Table 4 Research design and methods

2. METHOD

The study was developed by seeking for more understanding about factors of collaboration among craftsmen in HRC projects. The methodology contained:

- **Literature Review** | A survey of seventy-two (72) existing studies centred around collaborative working construction and several associated topics was conducted; forty-five (45) factors that support or constrain collaboration were identified through literature review
- **Field Observations** | Field studies on three (3) construction sites were undertaken and constraints of construction professionals were observed and evaluated; Users' functional and emotional needs and desires were identified using design thinking;
- **Interviews** | Twelve (12) interviews with domain experts involved in construction were conducted as main mode of data collection
- **Probabilistic Graphical Models** | A questionnaire was developed in order to validate the factors identified in interviews with three construction stakeholders (construction workers, construction managers, and technology providers) and the data collected was used for systemic models;

  Focus group experts collaborated to establish a Bayesian Network model, using the Causal Loop analysis model to develop an understanding of stakeholders' interdependencies and the role and responsibility of each in the entire system;

  A comprehensive framework for systemic interventions was in collaboration with four (4) domain experts developed using probabilistic graphical models (Bayesian Probabilities)

2.1. Literature review

Since the 1980s, evolving IT systems - in particular it's application in construction to improve project performance - was witnessed with an explosive growth and is currently a major field of academic research. According to Howard at al. the goal of most studies focused on the integration of data exchange, decision-making processes and knowledge to improve the efficiency in construction. In the last two decades over 200 published papers indicate an increasing trend in researchers' attention to IT in construction. According to D. Yu and J. Yang [23], 40 papers were published from 1995 to 2004.

The major topics were Knowledge generation and acquisition, KM approaches and knowledge-based systems [23]. The period from 2005 to 2011 has witnessed a boom of knowledge management research in construction. Over 100 papers investigated ontology, tacit knowledge, knowledge learning and sharing, as well as safety knowledge management and KM modelling [23] and in the short period from 2012 to 2015 over 70 papers studied the potential of ICT in construction.

Author / title	Research aim and method	Research purpose	Missing factors
M. Sarshar; U. Isikdag: A survey on ICT use in the Turkish construction industry	**Aim** | Identify the use and priorities of ICT to set agenda for future developments and directions **Method** | Literature research; Semi-structured interviews	**Technological** | Real-time access to information needed to aid collaboration (Collaboration was found to be one of most important issues) **Individual/ Social** | Challenges in implementation requires re-education and training to promote wide acceptance of ICT software	Target group managers in site office / head office (Site personnel excluded); Study collected data only from one stakeholder group (senior management) Further stakeholders suggested to be interviewed
S. Tai, Y. Wang, C.J. Anumba: A survey on communications in large-scale construction projects in China	**Aim** | Grasp the current status of communications in large-scale constr. **Method** | Survey by postal and telephone	**Managerial** | Organisational structure was identified to be linear with many middle-level workers with the result of information distortion; as a labor-intensive industry with relatively low levels of knowledge ICT implementation has lagged behind compared with manufacturing	Study limited to Chinese market; More stakeholders might be to consider; technological factors not investigated but only social/ managerial factors;
Shelbourn, Mark, Bouchlaghem, NM, Anumba, Chimray, Carrillo, P: Planning and implementation of effective collaboration in construction projects	**Aim** | Address the pairing of technological issues with organisational and people issues to enhance collaboration **Method** | Literature search; semi-structured interviews; questionnaire; framework for implementation of collaboration	**Individual/ Social** | Collaboration devised into: Vision; stakeholder engagement; trust; communication; processes; technologies **Other** | A conclusion was drawn of what the industry's requirements are: Model; process; standards; good practice; design; legal aspects;	Study defines collaboration on the organisational level while pairing 'business, people, technology' (Technology push) Further investigation on the level of craftsman might assist in developing a clearer understanding of factors underlying ICT implementation

Table 5.1. Literature review related to ICT and collaboration in construction

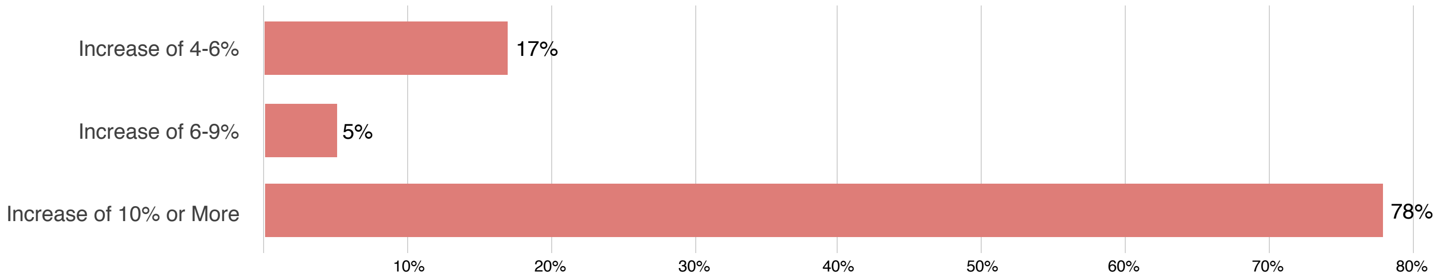


Fig. 6.1. Projected requirement of skilled trade workers three to ten years

While major topics such as knowledge sharing or knowledge-based systems were still actively discussed, new topics were BIM and big data technology, social techniques, and collaborative KM. Y. Chen, and J. M. Kamara described the nature of previous research as driven by "technology push", investigating solutions to particular industry problems. Actual ICT implementation involves both technical and social issues and studies in the past focused rather on the technical side. More recent research led to the conclusion that social factors such as motivation, user characteristics, their attitudes towards new technology and training and support are dynamic factors and crucial for an effective ICT implementation in construction.

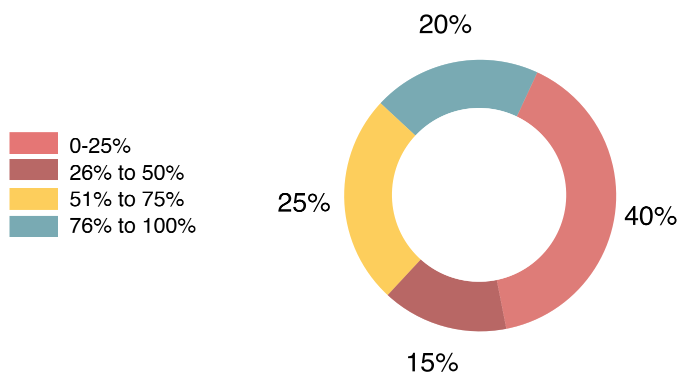


Fig. 6.2. Percentage of work that is self-performed

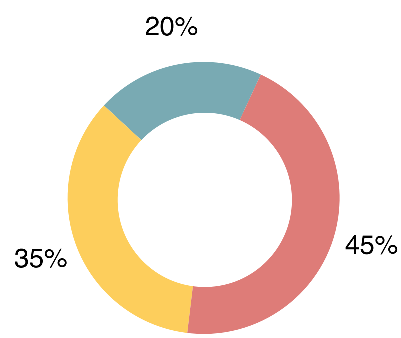


Fig. 6.3. Plan to increase the amount of self-performed work in future

Most studies reviewed spent their major focus on Information sharing software that enables other computer applications to access the same information. And this applies, as learned before, mainly for site offices and head-offices but less for building sites. The results obtained by FMI Corporation in 2016 suggest that while executives and managers, particularly senior and project managers are well equipped with latest ICT solutions, it is the field labor where integration is lagging. FMI also revealed that 78% of the largest contractors in U.S (annual revenue of USD

500 Million to USD 5 Billion and above) expect to increase the level of skilled trade workers by 10% or more in the next 10 years as seen in the figure below. One contributor to this expected large increase of requirements is that 45% of the companies surveyed expect to increase the amount of self-performed work in future [21]. In recent years, most large contractors increase the amount of self-performed work. In other words, companies have taken the role of construction managers and hiring sub contractors to do the work as needed. Too high was their dependency on sub contractors's ability to hire and train tradespeople to get the job done. In order to gain more control over projects' quality and profitability, the majority of companies polled in the survey of FMI are strategically looking at expanding their capabilities to self-perform.

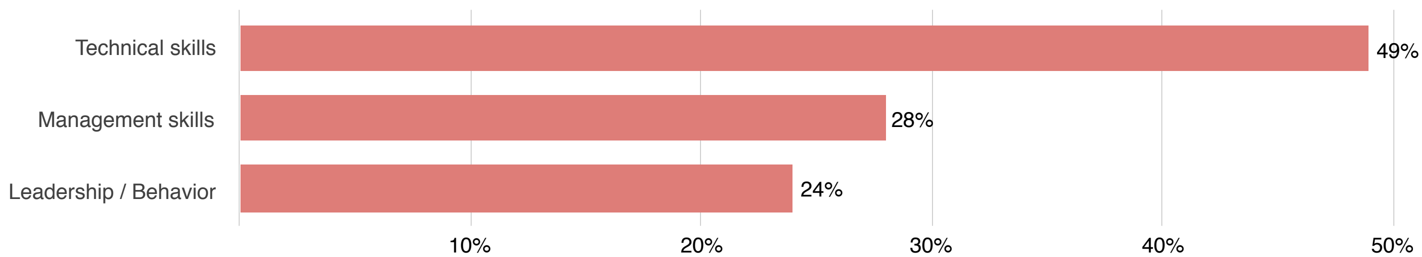


Fig. 6.4. Impact of business if companies cannot reasonably meet the need for skilled labor and tradespeople in the next view years (FMI Survey Report 2016)

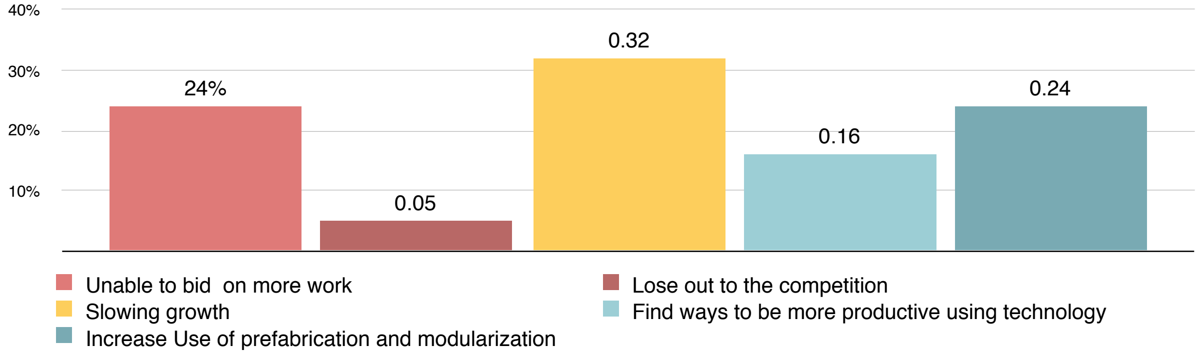


Fig. 6.5. Impact of business if companies cannot meet the need for skilled labor

Rich Henry, vice president of human resources at McCarthy Building Companies, Inc. suggested "The ability to self-perform work has always been at the core of our mission, enabling us to offer clients an effective option for project delivery. Now more than ever, clients are looking for certainty. Having a trained and reliable workforce will be even more crucial for builders to be successful going forward" [21]. If contractors cannot reasonably meet the need for skilled labor, the response to FMI's survey revealed that 16% will find ways to be more productive using technologies (Fig. 5.4.). But, while the increased modernisation in construction projects is a trend that cannot be ignored, it is not a panacea for skilled labor shortage. Rather, with the growing use of technologies new risks such as finding and training personnel that are capable and willing to using them will impact strategy decisions. Even with an increasing use of new technologies, construction will remain reliant on skilled personnel to accomplish its tasks.

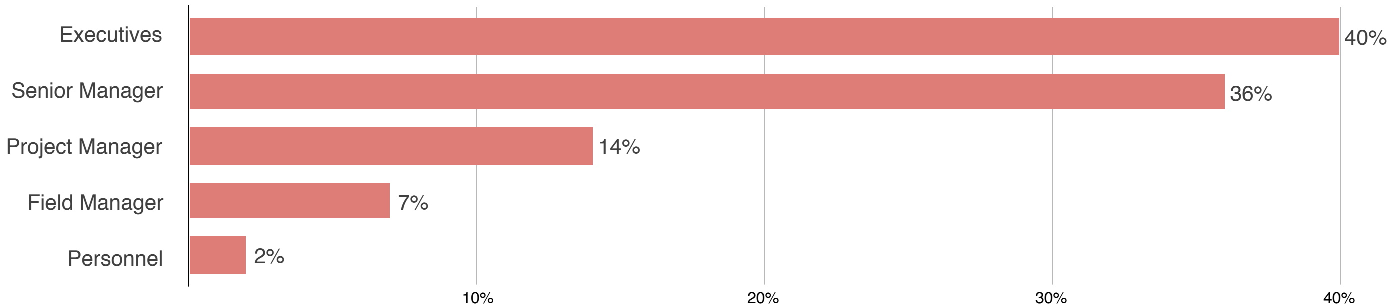


Fig. 6.6. Positions with well-defined succession plans

One industry specific problem, the report suggests, is its understanding of growth and demand. due to the current boom in construction projects, many companies are experiencing growth and want to self-perform more as a core strategy. But, the supply of qualified personnel is shrinking. How can this paradox we have already learned already in section 1.4.1 be bridged for future construction projects? Replacing retired talent will be more and more of essence for contractors and their talent pipeline needs to remain full. Having people trained and in place to succeed positions of top executives and senior management has ever been a challenge in the industry. 76% of respondents from FMI's survey said their companies had succession plans in place for top management. However, only 14% have succession plans in place for key project managers, and only 7% have considered succession plans for field managers. Succession for skilled trade workers is barely considered at this time (see figure 5.5). This indicates a need for even smarter strategy and more efficiency in recruiting and retaining a top-skilled labor force.

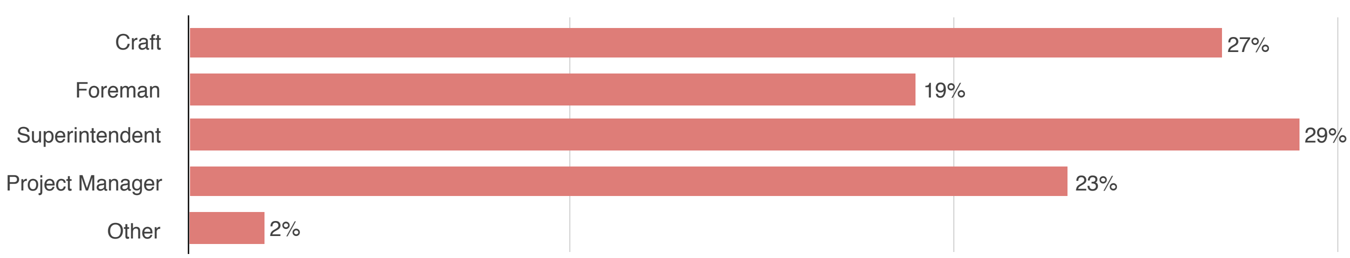


Fig. 6.7. Positions facing skilled labor shortages

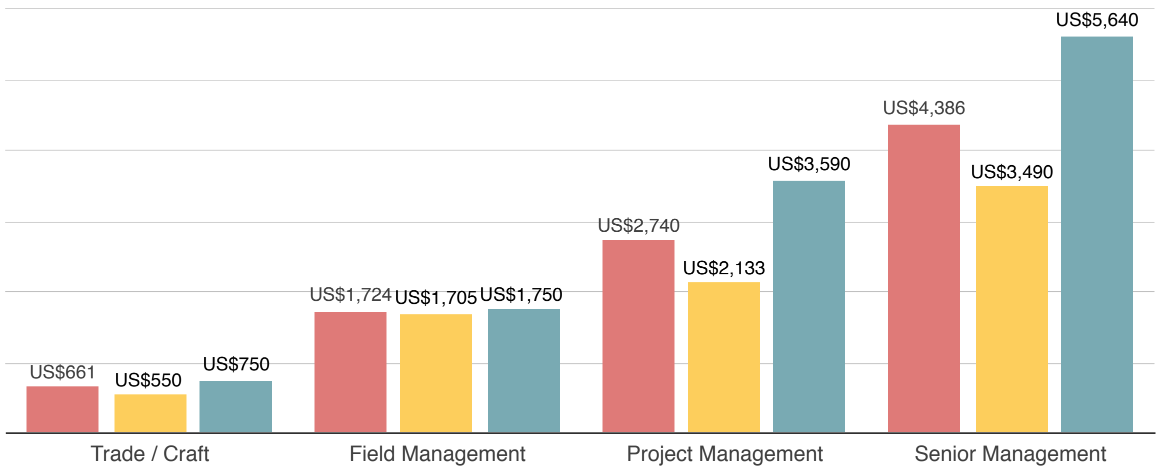


Fig. 6.8. Average company-spending on training (Annual $ per person)

Total   Low Self-performing Contractors   Self-Performing Contractors

In this survey and in related references it was observed that companies will need to model many of those efforts in place to find, train and retain top managers to similar plans as to those who perform project work. Driving factors behind or their impact on the skilled labor shortage is not of high relevance for this study. But, observing the particular position being the most exposed to it, we can see that construction's workforce on building sites is the most vulnerable in the among all (figure 5.6). Training costs for field supervisors and skilled tradespeople will likely increase [21]. Companies that self-perform more than 50% of the project are currently spending more per trainee than companies that perform less than 50%, according to our survey of large contractors. However, all those responding took in a minimum of $500,000,000 in revenues last year, and most had annual revenues over $1 billion. The dividing line for the chart below was companies currently self-performing over or under 50% of their projects.

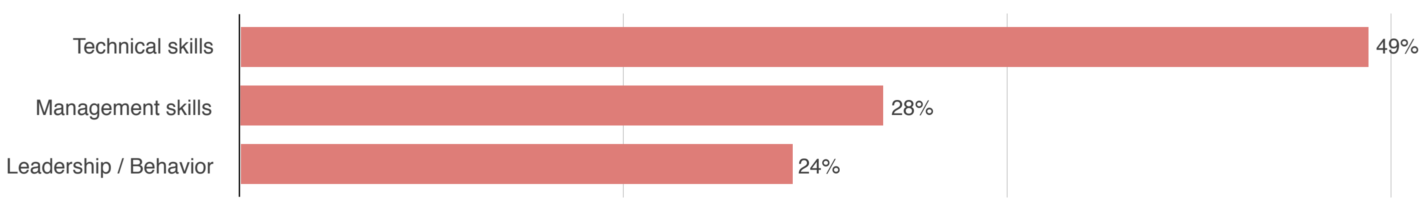


Fig. 6.9. Proportionate mix of training and development provided for field management

Although this small representation is difficult to project to the whole industry, it is likely companies that are working to become industry leaders will need to spend more to train their field personnel in both the basics and the "company specifics." The company way includes those areas in which the company intends to excel and bring everyone into the company culture, such as areas like safety or teamwork.

A comprehensive review of existing studies centered around collaborative working, current available technologies, and several associated topics was conducted. Since the 1980s, evolving IT systems - in particular it's application in construction to improve project performance - was witnessed with an explosive growth and is currently a major field of academic research. Studies screened indicated a focus on the integration of technical solutions and along with it data exchange, decision-making processes and knowledge to improve the efficiency in construction. In the last two decades much literature indicate an increasing trend in researchers' attention to IT in construction. In the 90s and millennial decade, knowledge generation and acquisition as well as multimedia applications have attracted much effort from researchers. The period from 2005 to 2011 has witnessed a boom of knowledge management research in construction. Papers investigated ontology, tacit knowledge, knowledge learning and sharing, as well as safety knowledge management (KM) and KM modeling and in the short period from 2012 over 70 papers were found that studied the potential of ICT in construction.

M. Sarshar and U. Isikdag assessed the awareness and use of ICT systems within the Turkish construction industry. The paper explored the uses and needs of ICT with the aim to assist in setting an agenda for future developments and directions. The authors conducted a literature search on the global directions and needs for ICT within the construction industry. This was followed by semi-structured interviews to establish how Turkey fits into the global picture. For discussion, the authors suggested that the industry is aware of the benefits of multi-media applications but lacks of trained employees. Priority topics were multimedia applications, employee collaboration, office automation systems, ICT training activities, real-time access to information, knowledge warehousing, technology training, and information loss. The study concluded that Turkey has similar communication problems as other countries. Furthermore, with the absence of trained staff, technologies might be under-utilised and draw the critical conclusion that ICT education is critically important for the industry to uptake future technology development.

The study lied its focus on socio-technological factors of ICT adoption in construction projects and their originality is given by considering both technology trends and priorities by the industry. However, the authors only considered senior management as representatives for users of technology services. Furthermore, the paper did not consider the term 'collaboration' to happen on the actual construction site but rather in the site office or head office. Further study might be required to understand adoption factors by the users namely construction workers and buyers namely construction managers. S. Tai, Y. Wang and C.J. Anumba in 2009 revealed that 55 per cent of information communication were completed over face-to-face (FTF) meetings; 26 per cent through letters, while telephone and fax had 10 per cent and 5 per cent respectively. 79 per cent of communication, the study suggests, was paper-based while only 8 per cent were electronic. The paper clearly identified the communication problems and their roots caused by: 'Lack of good communication mechanisms'; 'Weak organisational structures'; 'Lack of support for advanced communication technologies'. With their extensive surveys, the authors present the direction for further research to improve communications in large-scale construction in China. The study suggests that problems are caused only on the managerial level and did not define the nature of communication. Thus, this paper argues that further study on large-scale construction projects is needed to investigate the different forms of communication and the factors underlying latest technology. This paper was only studying the Chinese construction industry and only stakeholders within the construction management.

The research by Shelbourn, Mark, Bouchlaghem, NM, Anumba, Chimray, Carrillo, P led to the conclusion that social factors towards new technology as well as managerial issues are necessary factors to add to technology strategies for effective ICT implementation in construction. Their major focus lied on a socio-technical approach to plan effective ICT implementation in construction. Hence, the outcome displays a decision-making framework to aid the development of strategies. And this applies, as learned before, mainly for site offices and head-offices but less for building sites. Further research might consider the real user of technology and thus, pay additional attention to construction workers.

Y. Chen, and J. M. Kamara described the nature of previous research as driven by "technology push", investigating solutions to particular industry problems. ICT implementation, however, does not result from the implementation of information technology systems alone . Thus, both technical and social issues need be considered and studies in the past focused rather on the technical side. Having a trained and reliable workforce will be even more crucial for builders to be successful going forward" . If contractors cannot reasonably meet the need for skilled labor, the response to FMI's survey revealed that 16% will find ways to be more productive using technologies. But, while the increased modernisation in construction projects is a trend that cannot be ignored, it is not a panacea for skilled labor shortage. Rather, with the growing use of technologies new risks such as finding and training personnel that are capable and willing to using them will impact strategy decisions. Even with an increasing use of new technologies, construction will remain reliant on skilled personnel to accomplish its tasks.

Literature Review (72 papers)	Technology characteristics	Improve efficiency	Data exchange	Collaboration workforce	Missing aspects
Nash Dawood, Abi Akinsola, Brian Hoobs (2002)	●	●	●	○	No other aspects than technology investigated
Charles O. Egbu (2004)	○	●	○	●	No tech. investigated
Yuan Chen, John M. Kamara (2011)	●	○	●	○	Studies aimed at impr. information flow but not collaboration
Changyoon Kim, Taeil Park, Hyunsu Lim, Youngkwan Kim (2013)	●	●	○	○	
Malte Brettel, Marius Rosenberg (2014)	●	●	●	○	

Table 5.2. Literature review (Comparison of papers studied)

One industry specific problem, the report suggests, is its understanding of growth and demand. due to the current boom in construction projects, many companies are experiencing growth and want to self-perform more as a core strategy. But, the supply of qualified personnel is shrinking. How can this paradox we be bridged for future construction projects? Replacing retired talent will be more and more of essence for contractors and their talent pipeline needs to remain full. Having people trained and in place to succeed positions of top executives and senior management has ever been a challenge in the industry. 76% of respondents from FMI's survey said their companies had succession plans in place for top management. However, only 14% have succession plans in place for key project managers, and only 7% have considered succession plans for field managers.

Succession for skilled trade workers is barely considered at this time. This indicates a need for even smarter strategy and more efficiency in recruiting and retaining a top-skilled labor force.

In conclusion of the above mentioned literature review, this study observed the trends in construction-communication related studies within the past two decades and investigated how the usage of ICT and workers' capabilities to perform has changed and is expected to change. It is clear from the research reviewed that for several years great effort has been devoted to the study of project characteristics in general and technology usage in construction in particular with the overall aim of maintaining or increasing quality. However, to the authors' best knowledge, very few publications are available in the literature that discuss the issue of ICT in regard of collaboration and communication of construction's workforce, rather than to share data and information.

2.1.1. Field studies on construction sites

Within the second stage of data collection, observations of construction professionals were undertaken on four (4) large-scale construction sites. Germany, Switzerland and Japan were chosen. For the success of the research method - particularly design thinking - the identification of users' functional and emotional needs were of the essence. Traditional IT development practices often focus on functional requirements of the end user and overlook their emotional needs with the consequence that solutions often fulfil all functionalities but fail to gain user adoption. Not only does design thinking focus on creating solutions that are human centered, but the process itself is deeply human . Hence, the objective of conducting filed studies was to understand intuitive communication patterns in use, as well as the real behavior of construction professionals in their natural environment, and than identify possible improvements. A logistics worker on a building site in downtown San Francisco - held anonymous -would appreciate a headset to safe time in scheduling deliveries and getting instructions. He reported to used his private smartphone on site and often gets interrupted by intense noise. He argued that if the device would be company-owned, or in other words, provided by the organization, he would use it more extensively since aspects of insurance and loss of sightliness would not be relevant.

The study has found that to keep construction projects on schedule and on budget, most effort is spend on the level of management. Construction workers propensity to self perform their work tasks and to collaborate with other firms operating at the site area seemed to be strongly associated with company culture. Here it is important to differentiate between the observed countries. While in Europe major obstacles were articulated by insufficient access to WIFI on sites and a general lack of information for construction workers, in Japan the problems were rather on the side of organizational information culture norms. In comparison with observations on European sites the Japanese construction industry was identified to be more likely ready to adopt mobile communication systems. Trade workers were generally satisfied with their accessibility to project-specific information and speed in reaching personnel. However, contrary to the statements given by construction professionals, very time-consuming acts of reaching remote colleagues were observed and the study concluded that by habit professionals not only tolerate but embrace the inefficient means of communication.

2.1.2. Interviews with domain experts

Semi-structured interviews with twelve board members and managers at large construction companies were conducted face-to-face in United States, Germany and Japan. Each interview lasted between 60 and 120 minutes, and were recorded. The aim was to get valid information on their observations, concerns, and expectations and thus, to test and improve the study's hypothesis.

Raymond LaTour, IT manager at McCarthy Building Company Inc. in Newport Beach, Los Angeles, stated that with the significant shrinking labor force organisations need to build their own sustainable corporate culture by promoting and training its field personnel. By implementing the right technologies to the right trades, he pointed out that pull-planning, a collaborative approach that includes those who are directly responsible for supervising the work on the project, is a powerful tool using post-it notes, color markers and white boards to create mutual understanding, commitment, and satisfaction. This sessions require the following phases:

- Invite the people who will be the last planners
- Share the conditions of satisfaction for the milestone with all the last planners
- Brief the whole group on all the work going on in the phase
- Have each last planner study their scopes

Responsible for these sessions are not any trade foreman or design lead, nor the supervisor's supervisor. It is the person who will show up everyday with his/her workers who will perform the work in that phase. It is the last planner - either project manager, field manager or superintendent - that knows the scope, the materials, the hours planned for the work and the equipment or information that is available or that is needed. Last planners need to understand what the starting conditions are for their work. This allows them to make requests and negotiate hand-offs during the pull planning conversation. It is therefore the last planner that needs to be equipped with new technology solutions, says Mr. LaTour and concludes the *next big thing* for the construction industry is to collaborate in real time with the entire team.

Richard A. Henry, president of the northern pacific division at McCarthy Building Companies Inc. in San Francisco explained, implementing technology down to the lowest end of construction personnel is strongly connected with the size of the organisations. While larger companies can afford to operate on the bleeding edge, testing the newest features, and often shape standards for technology usage, smaller companies add technologies rather because the clients they are associating with require them to utilise certain levels of technology. Once technology has been proven out in well recognised organisations as something that does improve efficiency it starts to tickle down throughout other companies. Pushing technology for enhanced communication down to level of individual craftsman is according to Mr. Henry needed to bridge the various cases in which work tasks are to be laid down. With providing technology to trade workers the capabilities including all elements of communication are provided as well. Some complexities tech suppliers might run into are limitations they have because of the migratory nature of tradesman.

The director of field systems at McCarthy's San Francisco office, David Burns, observed a general propensity for phone calls and face-to-face chat and calls this methods the rather more real-time versions of site-communication. Recent technology trends are rather utilised to capture and share data as to enhance communication between crafts and most efforts spent on the supply side support in preference phone applications with the idea that everyone possess a smartphone. Overall, Mr. Burns proposed a clear trend towards "much more mobile and much more connected" collaboration and communication on building sites and named the implementation of wearable communication technology in the level of field management the next progression in the industry. However, he said his company has not spent much effort in it in recent years and even has paused in a “wait and see” mode due to resistance from unions.

Despite all innovative technology ready, people are a very decisive factor, stressed Mr. Tanabe, ICT manager at Taisei Corporation in Tokyo. Even the best technology is of no use if people operating it do not function correctly. Fig. 7.1 shows the trend in both uploads and downloads of data in Taisei’s construction projects and indicates a clear increase of retrieving data while the uploads remain constant. According to Taisei, the willingness to share information is an expression of confidence that can only be established and maintained through focusing on the human aspects rater than the technical ones. In Japan Taisei increased the usage of headsets to increase the work time with free hands while coordinating work tasks. More important, however, is and will be the smartphone as one-fits-all product. Field Pad, an in 2009 implemented data-sharing platform contributed to a significant amount to the figure seen before and is used by every employee from the top to the bottom in Taisei’s corporate structure.

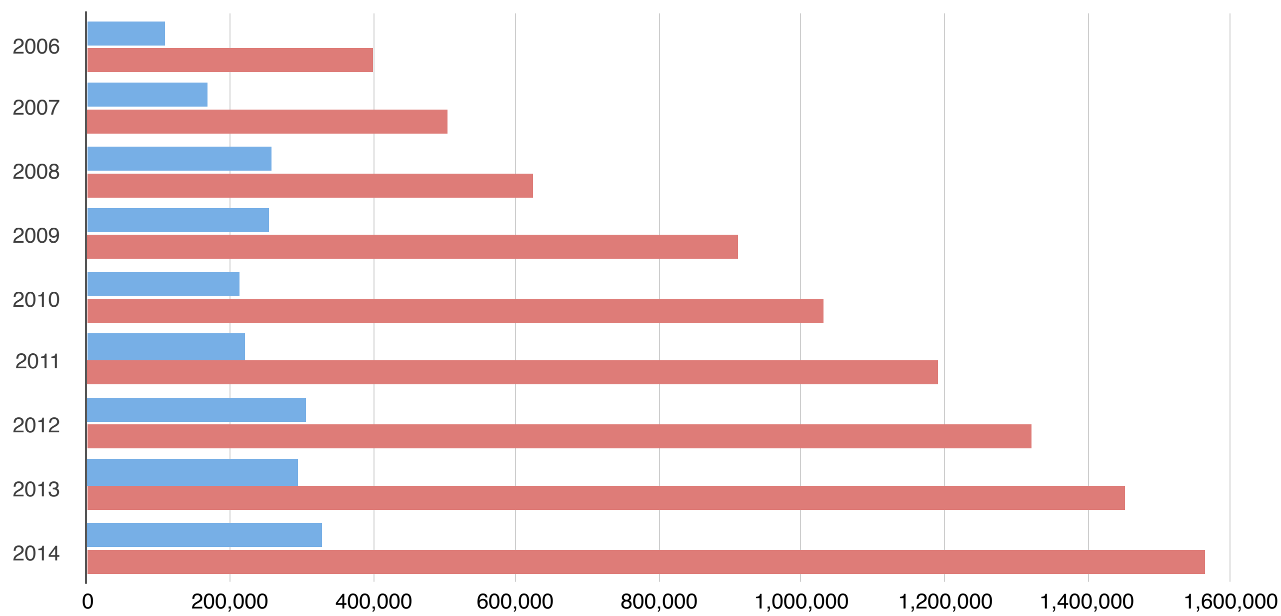


Fig. 7. Dynamics in file sharing in construction projects (Copyright 2016 Taisei Construction Co. Ltd.) Uploads Downloads

The construction industry in Japan, in clear contrast to Europe and U.S., faces no challenges with fully WIFI-covered building sites and as a result mobile applications, witnessing an explosive growth. Social Network Services such as *Line* or *Skype* are extensively used and allow real-time conversations with the direct sharing of images and videos. *Stacc,* entirely cloud-based, is the latest mobile application in Japanese construction (available since January 2017) and aims at replacing commercial SNS services. However, to increase collaboration in BC projects, the focus must not only lie on the technology itself but rather on its handling and therefore the human side, Tanabe said.

The key findings in the above interviews were that despite all innovative technology ready to this time, construction workers are the most decisive factor for technology adoption but barely considered. Additional, recent technology trends are rather utilised to capture and share data as to enhance communication between crafts. Most often, the interviewees associated the term “ICT in construction” with business information modeling (BIM), a software for the generation and management of digital representations of physical building models, information access and data sharing.

Fig. 2.1. 3rd Wearable Expo 2016 in Tokyo - Observation on technology trends in construction

Fig. 2.2. 3rd Wearable Expo 2016 in Tokyo - Photo by Victor Cuesta

2.1.3. Observation technology trends

A field observation at the world's largest exhibition for technology embodied in wearable gears were held in Tokyo, Japan. Tools, such as smart glasses, exoskeletons, smart watches, or health tracking devices have been presented for several industries. Broadly shown were internet of things (IoT) and augmented reality/ virtual reality (AR/VR) products for areas such as medical, welfare, healthcare, and entertainment, as well as manufacturing, logistics and transportation.

For construction the hart helmet dominated expectedly the products used and main topics were sharing of data and access information hands-free without the need to lie down the work task. It was identified that the organisations in their respective fields focused on hands-free technology to eliminate down time in construction projects. It was also has been found that the hard hat is the main device to mount tools for communication and information sharing. Similar to the domain expert interviews conducted, the observation on trends in communication technology concluded a clear trend towards information sharing and o the other side no particular trends in improving communication and collaboration. Technology cannot fix the social factors that constrain their usability, but it can impact how construction professionals work together to create an efficient working environment.

2.1.4. Questionnaire survey

A self-completion questionnaire with a total of 22 questions - including 4 key evaluation questions (KEQ) has been sent to construction companies via email. The chosen companies are located in Japan, Germany and U.S.A. but also South Korea, France and Spain and have a revenue between USD 2.8 billion and USD 15 + billion and are engaged in global large-scale building projects. In total 32 questionnaires were completed giving a response rate of 56 per cent. The data collected by the survey was analysed and used to determine the key aspects of on-site collaboration. These aspects were used as input data for the bayesian belief network model to develop intervention strategies for future projects.

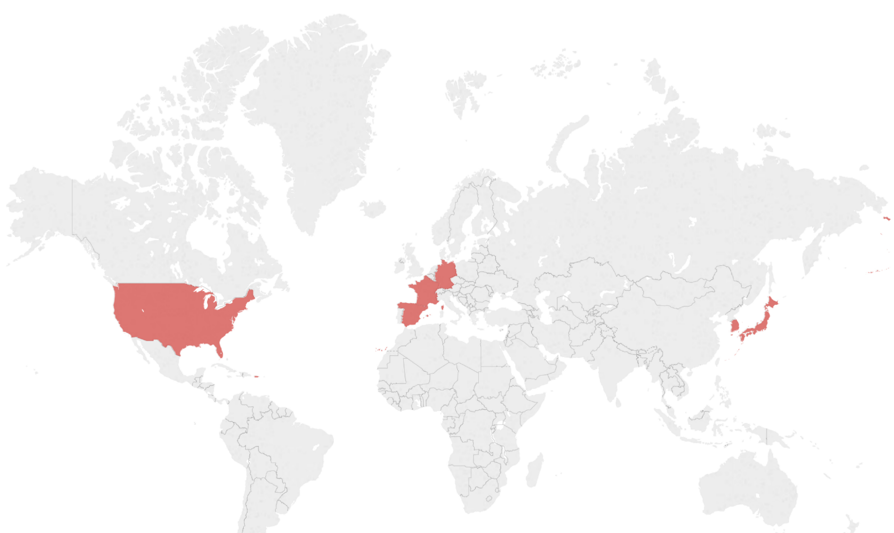


Fig. 8.1. Countries questionnaire was answered (France, Germany, Japan, Korea, Saudi Arabia, Singapore, Spain, U.S.

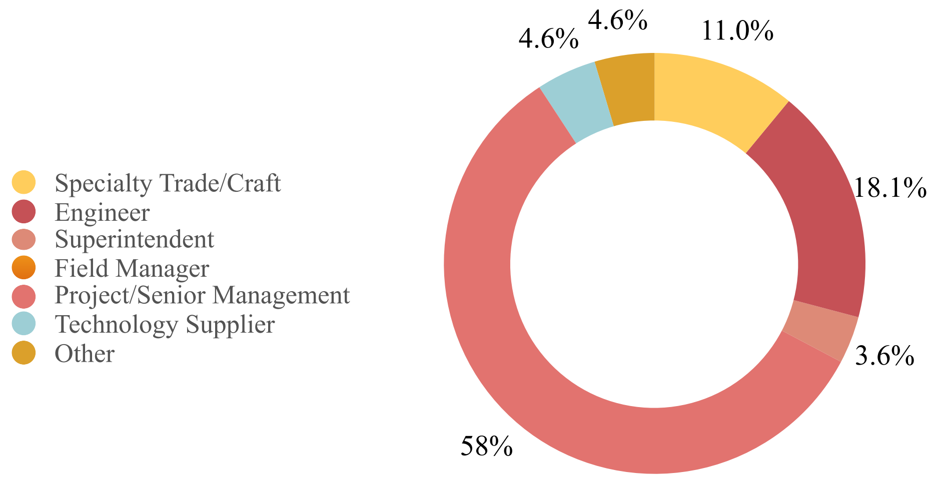


Fig. 8.2. Q2: Roles of questionnaire participants

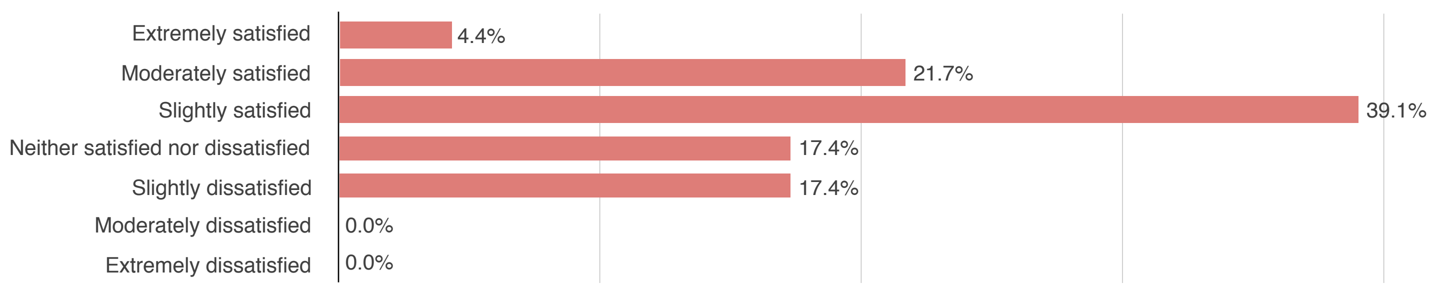


Fig. 8.3. Q3: Overall, how satisfied are you with the oral communication among special trade workers on building sites? (This includes communication within one company and between different companies)

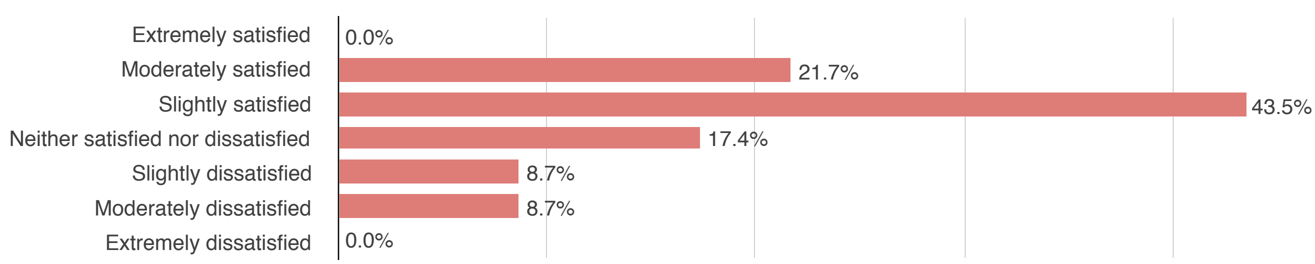


Fig. 8.4. Q4: Overall, how satisfied are you with the current exploitation of Information and Communication Technology (ICT) on building sites?

The questionnaire was divided into three sections and four sub-sections. Section one focused on the question of the current use of technology in construction projects and workers' accessibility to data and information. Section two observed organisations' propensities on both the acquisition and use of mobile communication solutions on construction sites. A special focus was given in identifying the biases between the implementation on building suites and site or head offices. Hence, the current use as well as expectations in future projects were questioned. The third section questioned about the potential of explicit trends and the agreement on the developed hypothesis.

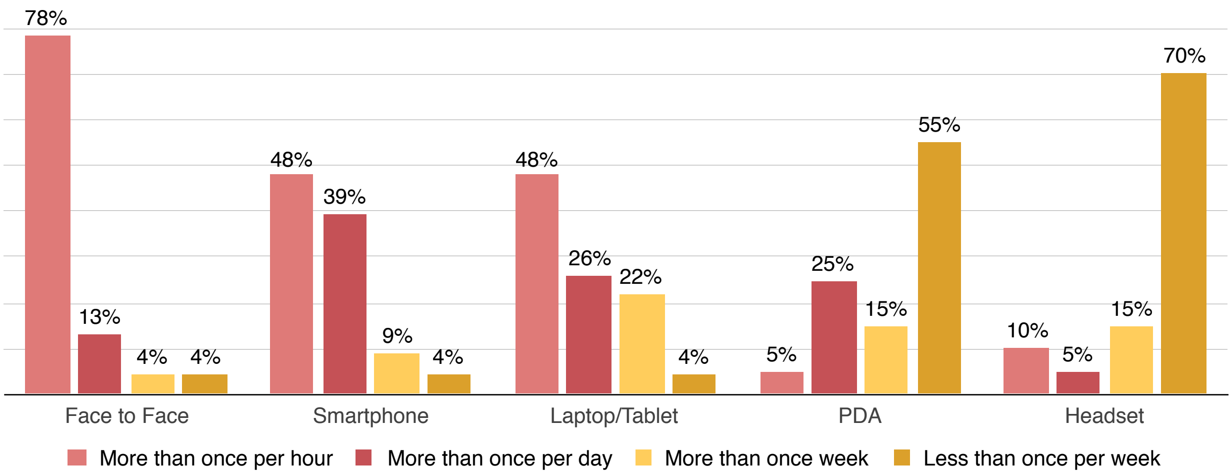


Fig. 8.5. Q5: In average, how often do you use the following modes/products to communicate with others on-site? Please check one box in each of the five categories.

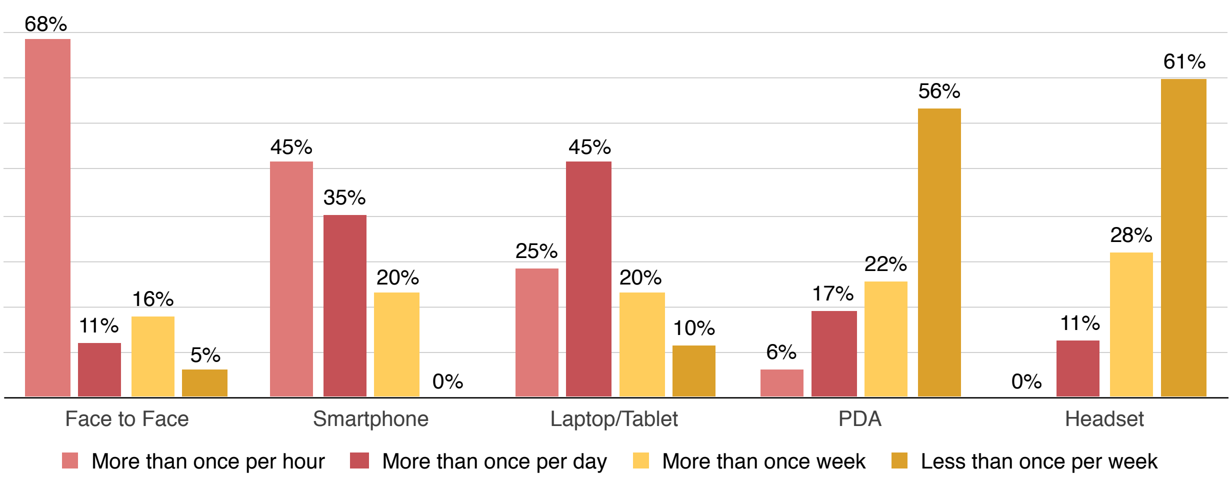


Fig. 8.6. Q6: In average, how often do you use the following modes/products to share information on-site? Please check one box in each of the five categories

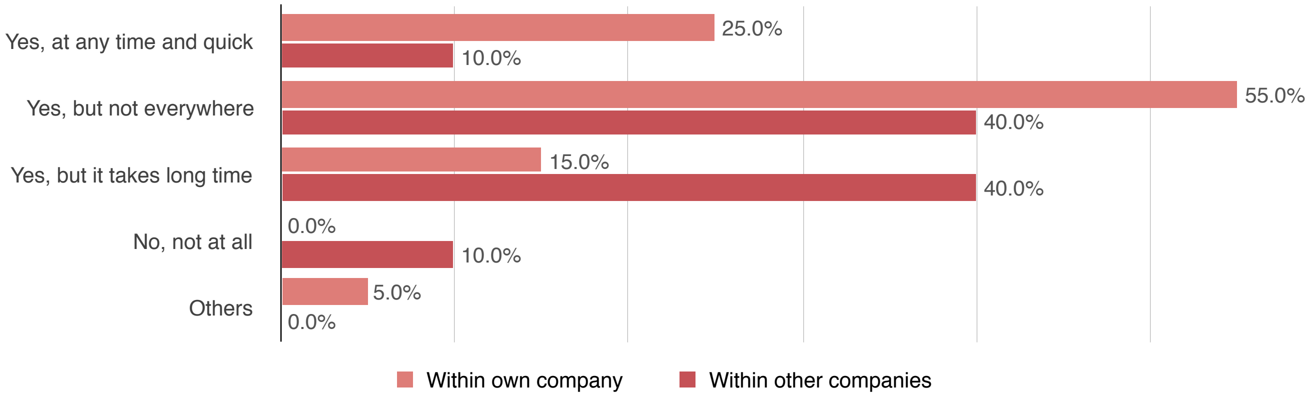


Fig. 8.7. Q7&8: In general, can you reach construction personnel within your company / of an other company on building sites timely?

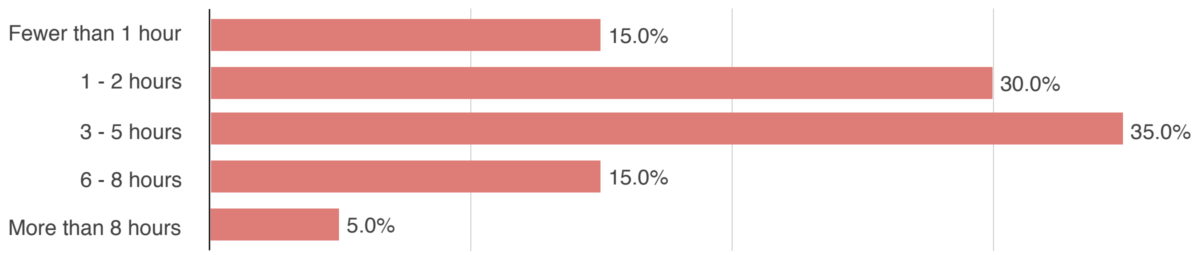


Fig. 8.8. Q9: In a typical day, how long do you use internet-based devices on building sites?

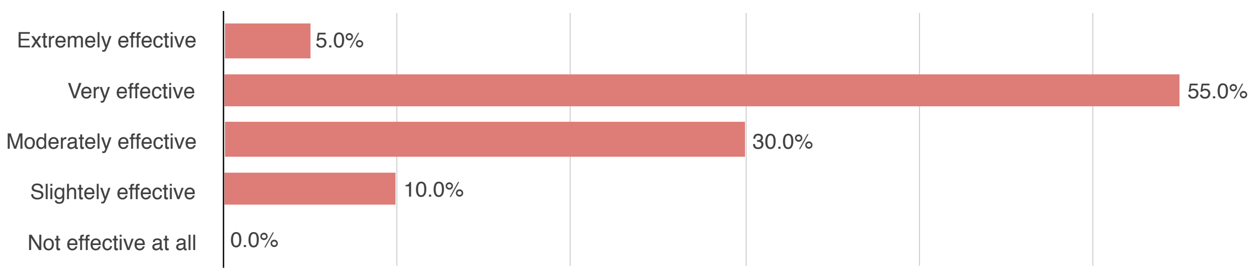


Fig. 8.9. Q10: Overall, how effective or ineffective is the current use of Information and Communication Technology (ICT) on building sites?

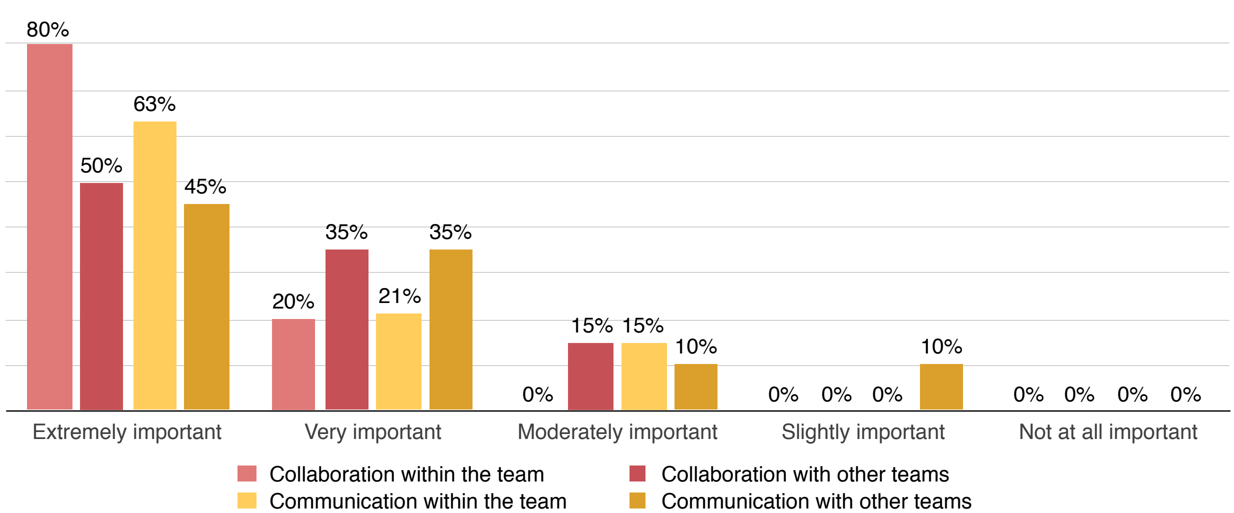


Fig. 8.10. Q11: In general, how important is effective and timely collaboration and communication between sub-contractors in future construction projects? Please check one box in each of the two categories

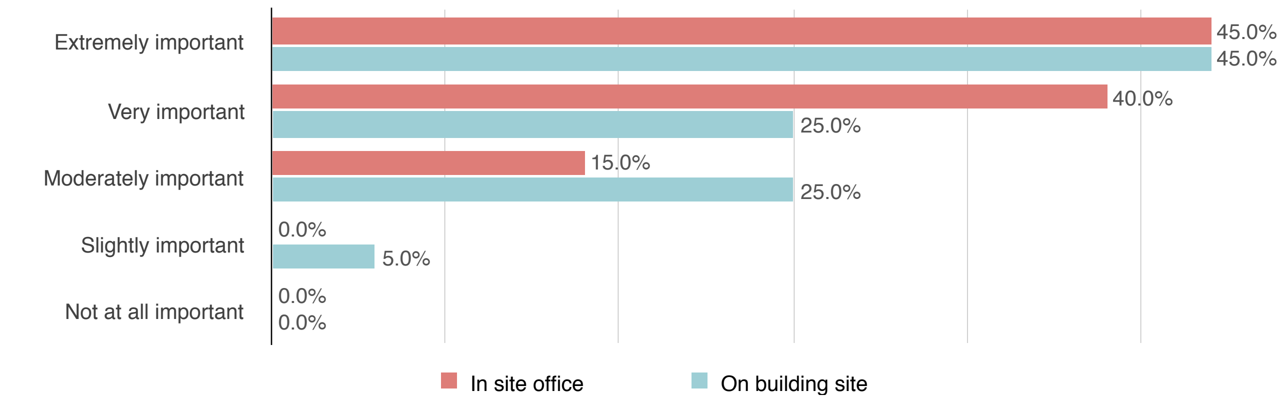


Fig. 8.11. Q13: Overall, how important is effective sharing of pictures and videos in future projects?

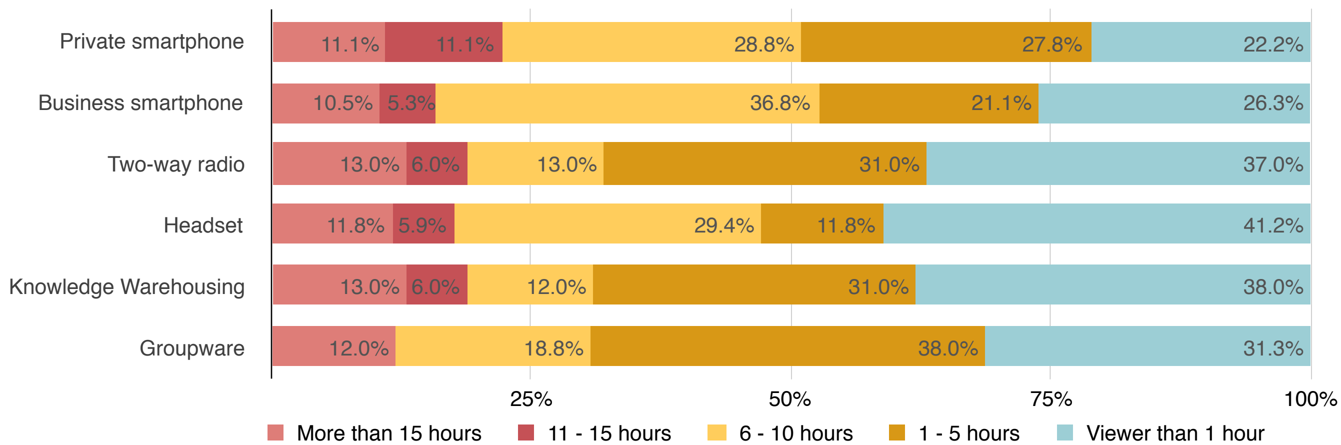


Fig. 8.12.1. Q14: In current projects on site, how often do you use the following IT-enhanced tools per week (In average)

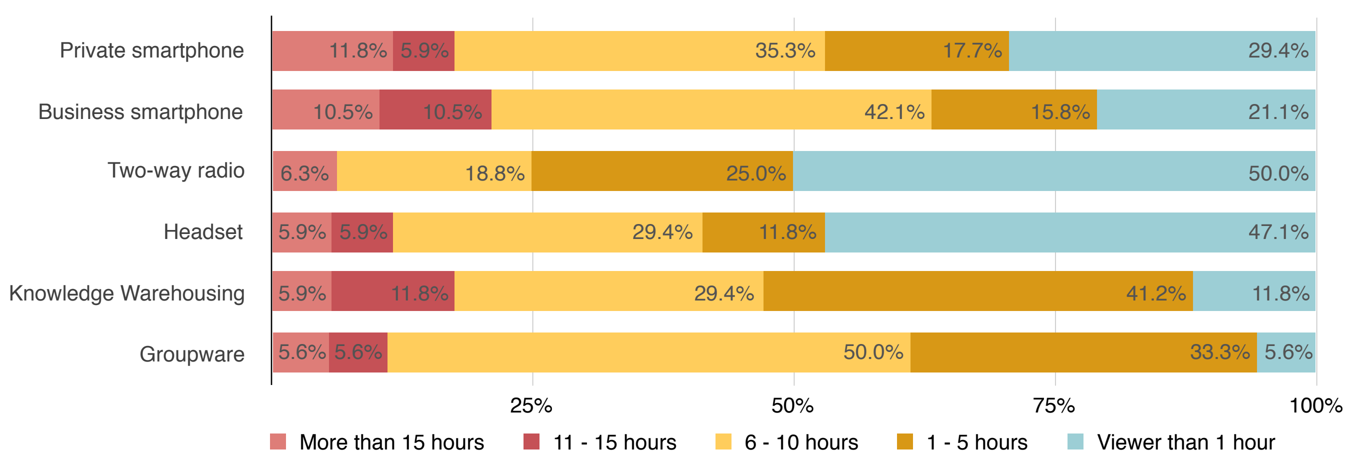


Fig. 8.12.2. Q15: In future projects on site, how often are you expecting to use the following IT enhanced tools per week (In average)

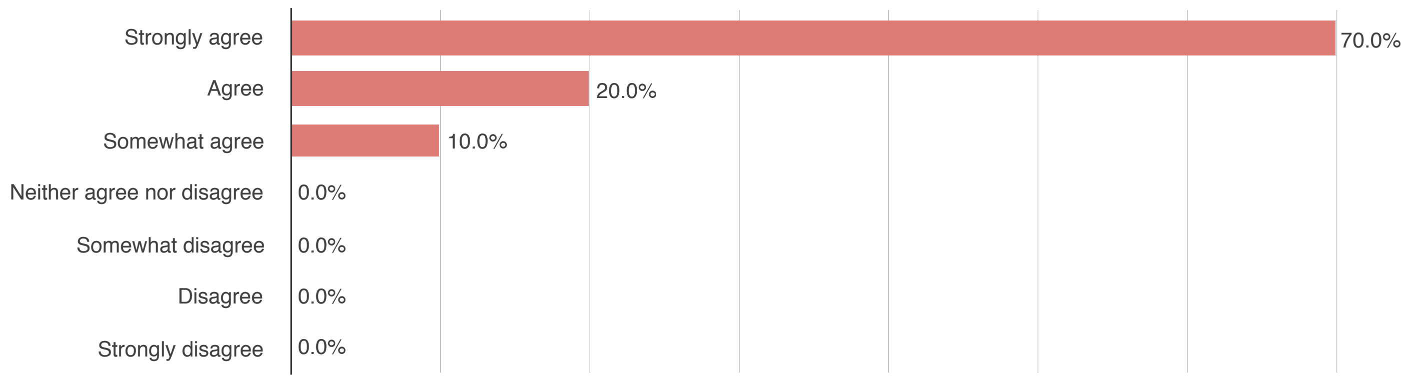


Fig. 8.13. Q16: In general, do you agree that field personnel must be more promoted and trained to meet increasing future requirements on their skill levels?

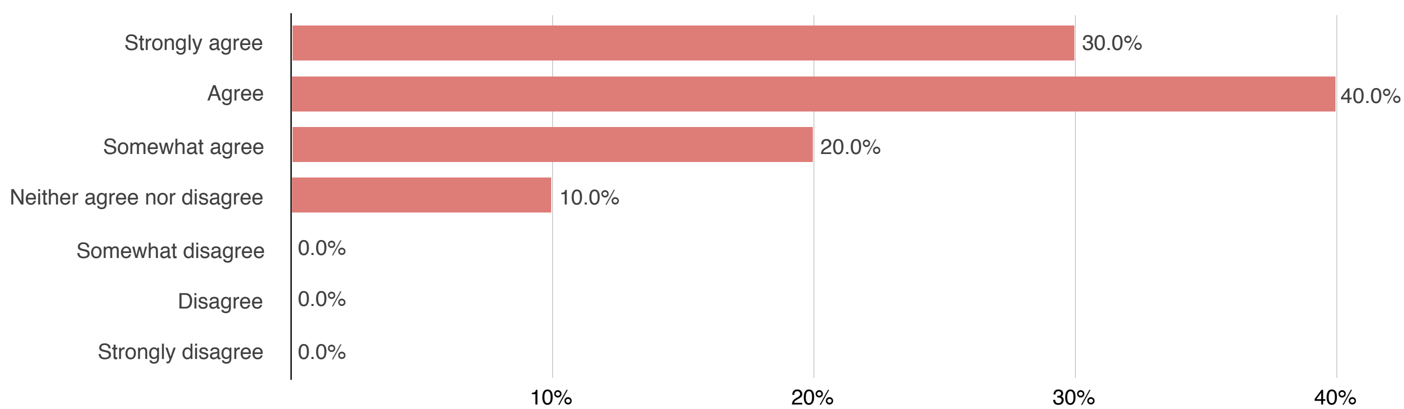


Fig. 8.14. Q17: In general, do you agree that enhancing the use of wearable technologies for individual craftsmen can bridge cases in which work tasks are to be laid down due to uncertainties or miscommunications?

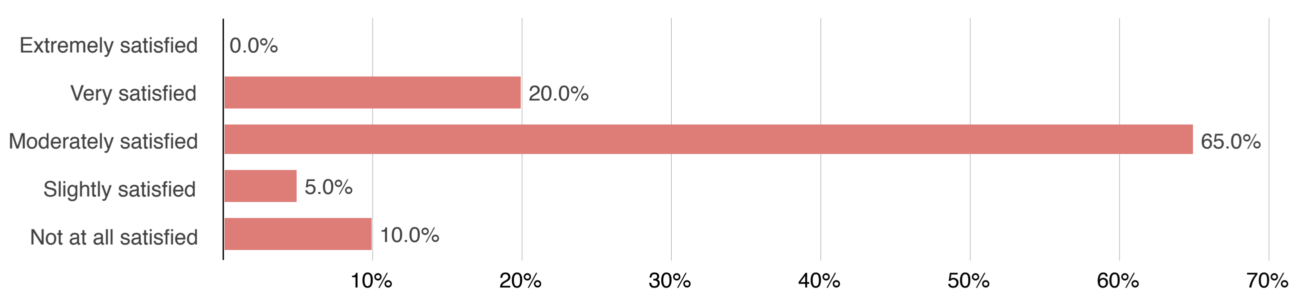


Fig. 8.15. Q18: Overall, are you satisfied with the level of access to project-specific information on building sites?

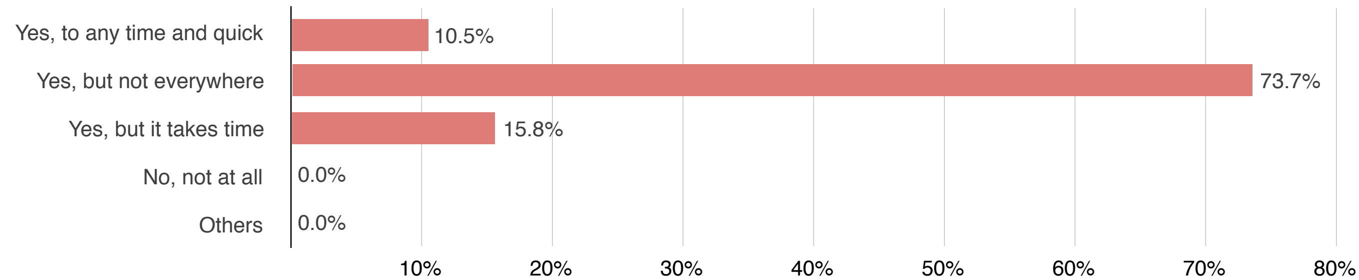


Fig. 10.16. Q19: In general, can you access to project-specific information on sites timely?

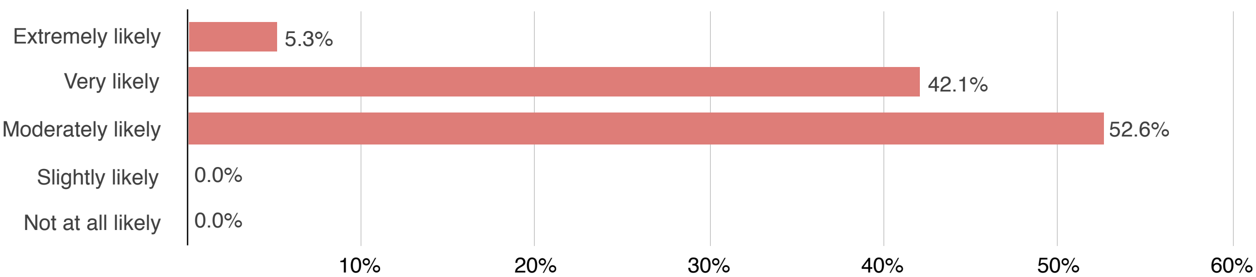


Fig. 10.17. Q20: In general, how likely is it to have access to the systems' data when working on building sites?

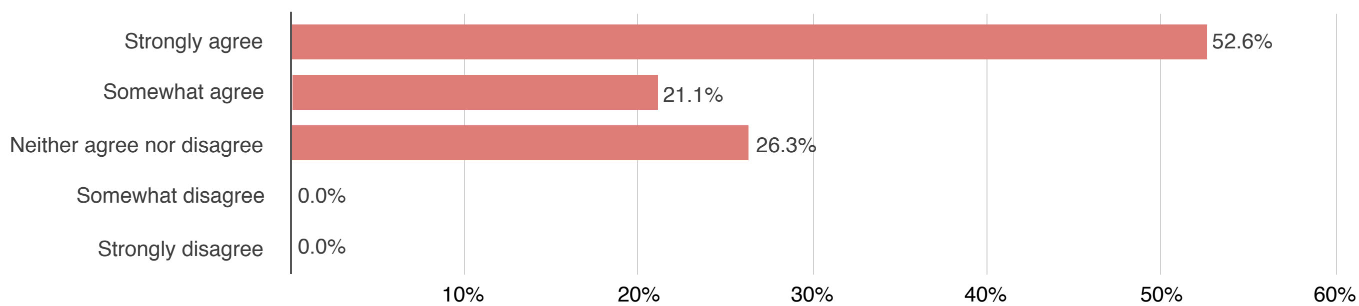


Fig. 10.18. Q21: Do you agree on the statement "Trade-workers need to access systems' data more effectively the next three to ten years when working on-site" or rather not?

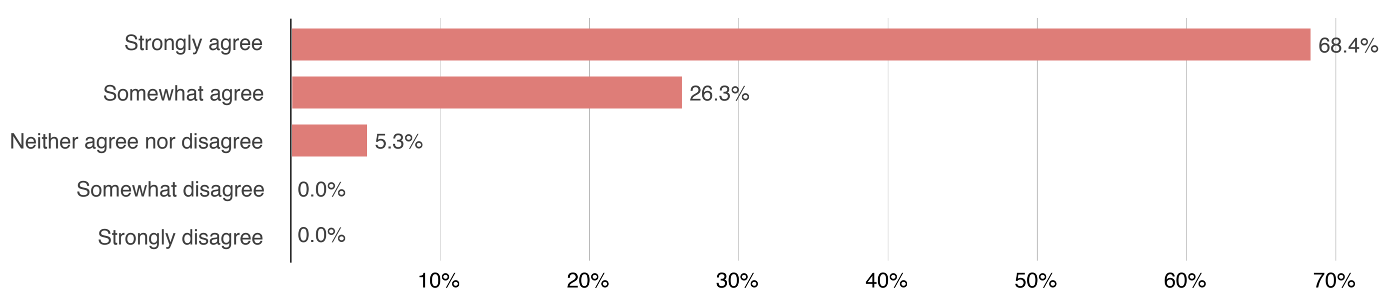


Fig. 10.19. Q22: Do you agree on the statement "Trade-workers need to collaborate and communicate more effectively in the next three to ten years when working on-site" or rather not?

The questionnaire survey identified key aspects to consider in planning effective collaboration in high-rise construction projects. The questionnaire respondents in this study revealed that the regular utilisation of two-way radios is expected to decrease from currently 19,0% to 6,3% in future projects. This decline of 66.8% indicates the further takeover of consumer mobile devices in voice-based communication in future BC projects. Here it is worthwhile to differentiate between the use of privately owned smartphones and company smartphones: As of today, respondents reported to use mainly their private smartphone on construction sites with 58,4%. Also for future projects expectations indicate only a slight trend towards the use of company-owned smartphones with a ratio of 54,3% to 45,7%.

The study revealed that pushing technology for real-time communication down to level of individual craftsman is needed to bridge the various cases in which work tasks are to be laid down today. Richard A. Henry from McCarthy Inc. indicated that by providing technology to trade workers the capabilities including all elements of communication are provided as well with the result of staying on schedule and on budget.

Constraints were found most significant in the migratory nature of craftsmen. Technology suppliers find it hard to identify required specifications and quality standards. However, this phenomena was only found in U.S. and Europe but not in Japan. The relationship between general contractors and sub contractors are entirely different for both cases (Please refer to section 2.2.)

2.2. Design thinking

The idea of design thinking expects to move along three spaces over the course of a project: An *inspiration* space in which insights are gathered from every possible source; an *ideation* space, in which those insights are translated into ideas; and an *implementation* space, in which the best ideas are developed into a concrete, fully conceived plan or action as seen in fig. 6.1. The design thinking process can be seen as a system of overlapping spaces rather than sequential stages of a lockstep methodology. Design thinking - constructive and experiential - addresses the needs of people who will consume a product or service and the infrastructure that enables it [24]. The paper serves as an introduction of the third generation of the IDEO process and emphasises the cyclical and iterative nature of the processes in correspondence with the further introduced action research process. By working closely with the field workers design thinking allows high-impact solutions to build up from below rather than being imposed or pushed from the top [25].

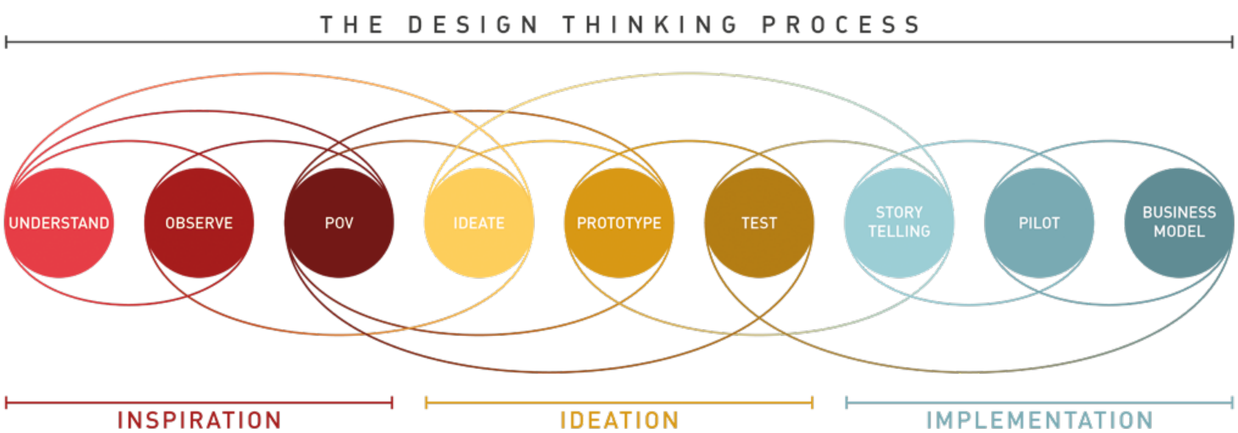


Fig. 9.1. Design thinking process

With the decade-long evolution of Design, the rise of *design thinking* is driving innovation and growth for the world's leading businesses, as well as governments, social systems, and on and on. While many companies hoped of *pushing* new technology into markets, today's attention must be shifted upward, from project teams and even individuals to organisations and not the other way around. The pairing of the rational and the creative is instrumental to achieving innovation and novel problem solving because only through a balancing of those two cognitive approaches ideas that balance the requirements of new innovations can be designed: making them desirable by people, feasible to produce, and viable as a business (fig. 6.2). What is needed is a serious commitment from the top of the corporate pyramid, and it will be repaid by better understanding from the base. By integrating what is desirable from a human point of view with what is technologically feasible and economically viable, design thinking approaches can ensure that every field worker involved in the project understands, appreciates, and has the ability to contribute to the overall vision of the company. moreover, to lead to general *integrative* thinking [24], not as a link in a chain but as the hub of a wheel.

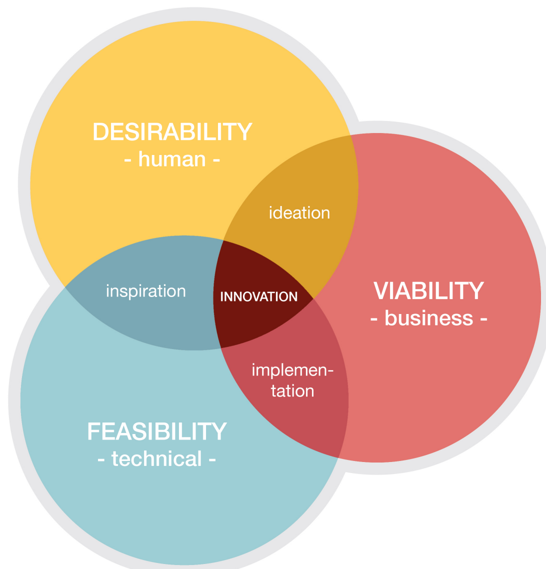


Fig. 9.2. Three innovation drivers in design thinking

Design can only happen with constraints and the willingness and acceptance of competing constraints is the foundation of design thinking. The *inspiration space*, the first stage of the design process, is mostly about discovering which constraints are important and establishing a framework for evaluating them. The mission of this first space is to explore and turn observations into insights. The sources of inspiration for innovation are multiple: Thinking about priorities and trends, observing and talking to the people to innovate for in their real environment, understanding the extreme users, and looking at the possibilities offered by using or combining existing solutions. The *ideation space* is the process of generating, developing and testing ideas that may result in solutions. Different methods of creativity are utilised, as well as fast prototyping and tests with users in their environment. The goal is to translate ideas into solutions. The *implementation space* begins at

Fig. 9.3. User road map (Given case to identify natural behaviours)

the moment when one or more mature concepts emerge from the interaction between the inspiration and ideation phases. It includes all the activities needed to convert the project from the design state to a reality. To make this transition successfully, the following elements must be combined: Persuasion, adapting the economic model, and obtaining approval from management to launch operations under the company's internal processes. But, design thinking is similar to other approaches limited in many ways. Since it has been introduced 15 years ago, the world has changed into one that produces 2.5 quintillion bytes of data; each day. So much data that over 90% of the overall data in existence was created in the previous two years alone [26]. Design thinking is described as one of the most important ideas of the 21st century. But, the complex and interconnected global system has pushed it to outreaching its usefulness. To continue the methodology's influence on business, design, and so on, design thinking needs now to look at a larger whole by incorporating another body of thoughts: Systems thinking.

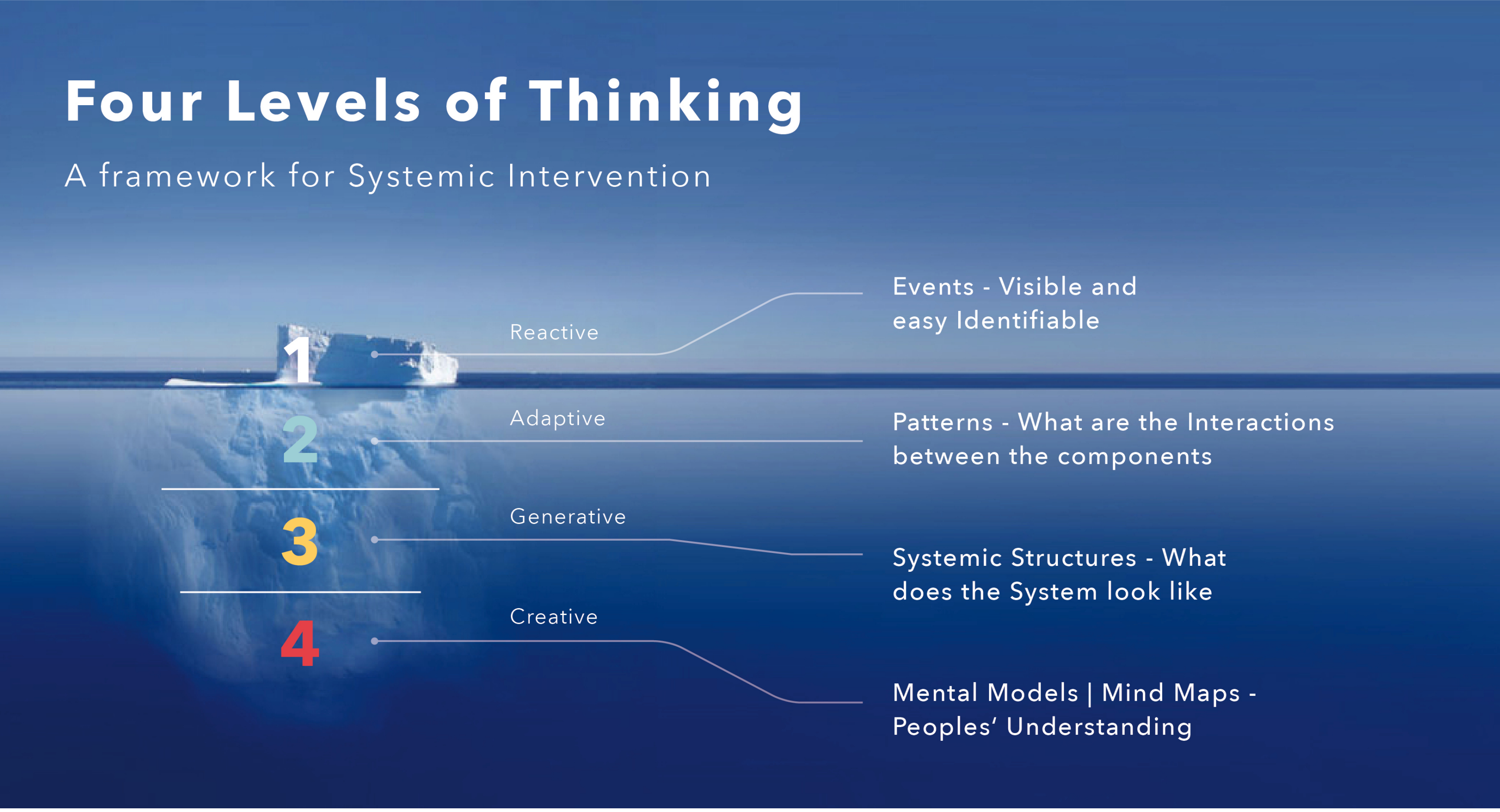


Image. 3. The Iceberg approach (K. E. Maani and R. Y. Cavana 2007)

2.3. Systems thinking

As earlier described in section 1.10, the core factors, that differentiate systems thinking and design thinking approaches are:

Design Thinking	Systems Thinking
Methodologies arose from the consideration of products, services and artifacts. The problems are ultimately resolved by designers by trade. The design team observes and studies the stakeholders.	Systems thinking methodologies arose from the consideration of social systems. The stakeholders are the designers

Table. 6.1. The Iceberg approach (K. E. Maani and R. Y. Cavana 2007)

Despite many efforts to deal with the various complexities in its typical fragmentation, construction is facing a number of challenges in cross-sectoral communication and collaboration as described in section 1.4. When observing failures it is easier to analyse the problems by braking the system down to smaller and smaller parts, going along with the risk to lose sight of the interaction between all the elements [16]. From a systemic point of view, communication can be seen as a part of a larger system, *construction* for example.

The term systems thinking is preferred to *holistic* or *whole systems* and emphasise understanding the whole rather than the dynamic structure of the system. It offers an holistic and integrative way of looking at all major dimensions of the complex problems in construction communication, and enables the design of effective and long-term management strategies. As a mode of analysis, systems thinking is used to understand and explain the set of relationships and consequences in any possible matter. It emphasises the emergent properties of the whole that nether arise directly, nor are predictable.

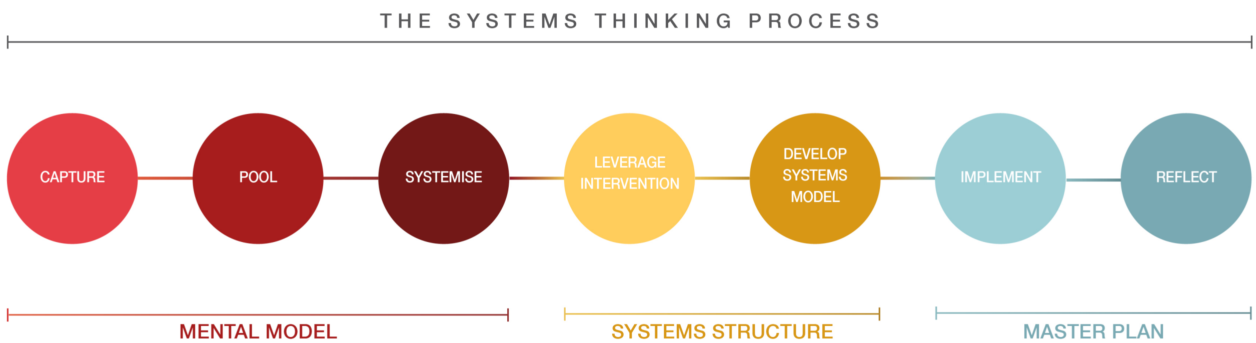


Fig. 10.1. Systems thinking process (Based on the Evolutionary Learning Laboratory framework, O. J. H. Bosch, N. C. Nguyen, T. Maeno, and T. Yasui 2013)

The vocabulary of formal systems thinking is one of causal loops, unintended consequences, and system dynamics. Before explaining about the analogies of systemic root-cause analysis and interpretive structural modelling it is important to understand the principles of systems thinking: Most commonly used is the analogy of an iceberg to illustrate the conceptual model known as the *four levels of thinking* as a framework for systemic interventions (Figure 6.3.). This model is a helpful exemplification to explain the concerns that drive systems thinking. The top of the iceberg - visible above the water level - marks “Events”, incidents that are encountered from day to day. Most decisions and interventions currently take place at this level [26], because it is easier to notice events than it is to discern hidden patterns and systemic structures. Maani and Cavana described this section therefore to be of *reactive* nature [27]. Systems thinking, however, starts at the deepest level (Fourth) of thinking: The mental models of individuals on building sites, in site offices, or at headquarters that influence why projects work the way they do. Mental models reflect the beliefs, values and assumptions that people do and are the first part of systemic structures. The values of individuals are the basic for mental models and this indicates the need of design thinking as important enabler to create them. The systems approach starts when seeing the world through the eyes of others. Therefore, this level's goal is to capture all the different mind maps to then pool them into a systemic structure as described later in this section.

Not just what happened and when, but rather how and why problems arise, is explored after the *creative* level. Systemic structures - generative in nature - explore the interconnectivity of components and resulting out of their feedback loops, which change the behaviour of the system and even define them. now, in the third level of thinking it is about to understand how the different mental models can be integrated into a systemic structure that reveals how the different components inter-relate and effect one another. Moving on to the second level of thinking, we explore and identify the patterns that emerge when a larger set of events becomes linked. Particularly leverage points are of high importance to understand and build integrative systemic interventions.

The study comprises a comprehensive systems thinking framework as seen in figure 6.4, designed to deal effectively with complexity [16]. In this approach, which is as virtual (a way of thinking; a concept) as real (individuals coming together to work for consensus), all stakeholders involved develop a deep understanding of the system in form of a large mental model, a shared vision for systemic innovation and improvement [16]. The process is a unique method to collaboratively integrate diverse knowledge to help manage complex issues. In this study, all stakeholders covered were closely involved to design a systemic root-cause analysis (Fig. 7.). Decision makers on both demand side and supply side collaboratively moved down to the deeper levels of thinking and providing the systemic analysis in which the interventions were identified to a later stage. This paper is the first to demonstrate how a comprehensive systems thinking approach and design thinking approach can be used to deal with the complex issues of IT-enhanced collaboration in construction. The systems thinking approach, based on the Evolutionary Learning Laboratory framework, starts with the first phase in which groups of experts capture the mental models of all stakeholders involved. This stage relates to the deepest level of thinking in the Iceberg model.

Here it is crucial to consider the perception of *everyone* related to BC projects from the top to the bottom of the organisational hierarchy, the industry, suppliers, unions, and on and on. That following, the various mental models are pooled and extended into a systems structure. The systems simulation software *Vensim* is used for the design of a systems model (Causal Loop Diagram) to integrate stakeholders' diverse mental models and identifying the interrelation between them.

Once completed, the model assists to develop an understanding of stakeholders' interdependencies and the role and responsibility of each in the entire system. The main barriers as well as drivers of the system are discussed in detail. This provides stakeholders the opportunity to gain insights on the implication of coordinated actions, strategies and policies [16]. In other words, this process provides them a better understanding of each other's mental models, which leads to the identification of leverage points for systemic intervention. Leverage points in a systems are so-called "points of power", elements where systemic interventions can create improvements and contribute to the solving of problems or achieving goals in the system. The outcomes are used to refine the systems model and form an integrated systemic master plan with defined goals and strategies (systemic interventions).

Bayesian Belief Network (BBN) modeling is used to determine the leverage points that influence the factors that could affect the expected outcomes to ensure maximise impact and control. Once the systemic interventions have been identified and an operation plan has been designed, the third phase "*master plan"* is to implement the strategies and, because of systems' typical complexity and uncertainty, reflecting and determining how successful or unsuccessful the interventions are. Unfortunately we cannot simply discern others' mental models; any collaboration and consensus of individuals is a matter of shared experiences and the result of honest discussion and understanding. The main stakeholder in this research, construction's workforce, the management and technology providers have individual mental models of the system "Construction" depending on their experiences, goals and understandings.

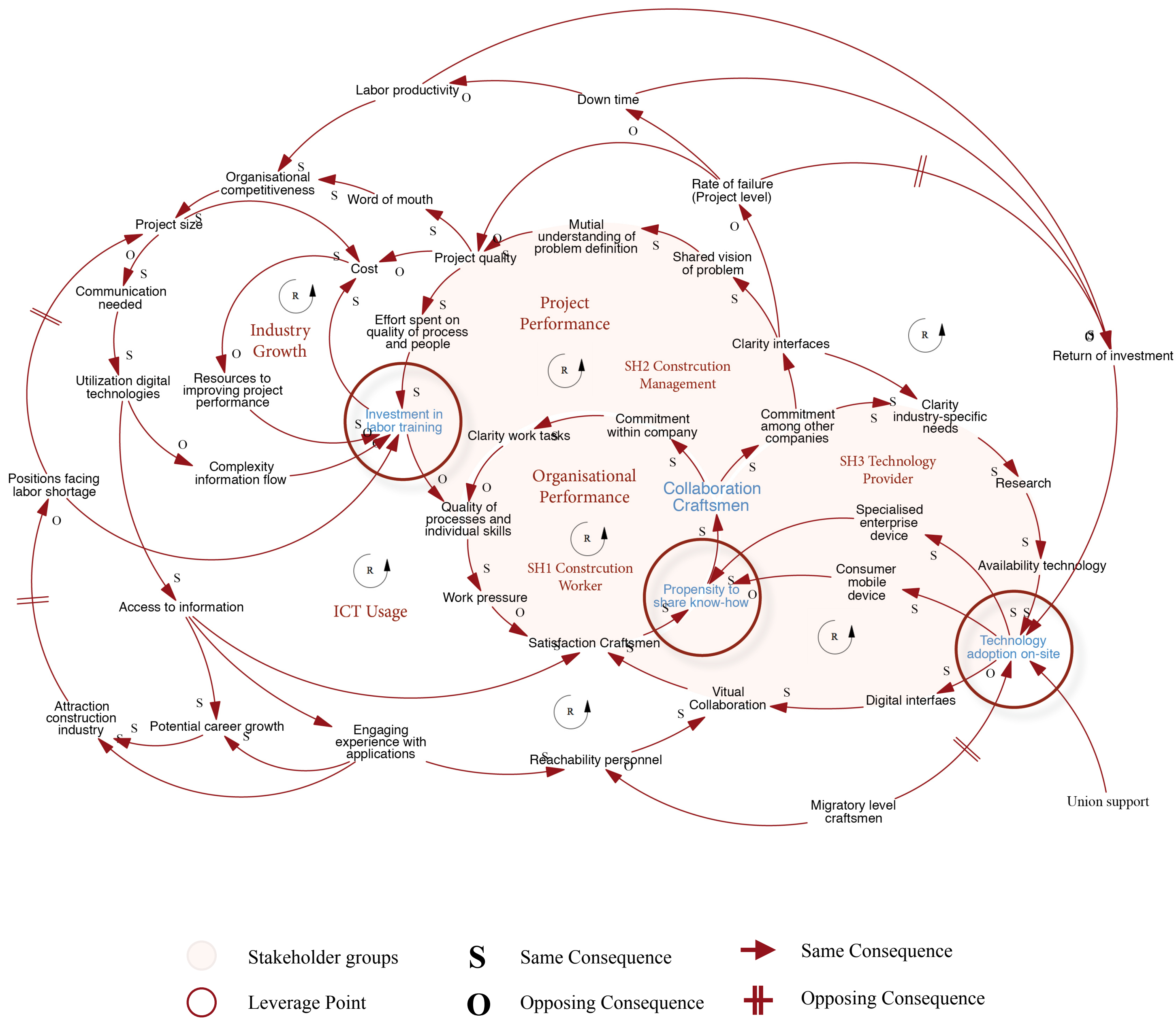


Fig. 7. Causal Loop Diagram with three (3) identified leverage points

2.3.1. Causal loop diagram

Causal loop diagrams provide a language to articulating our understanding of the interconnected nature of our world. We can think of them as sentences which are constructed by linking together key variables and indicating the causal relationships between them. By connecting several loops, we might create a coherent story about a particular problem or issue by considering the big picture. In other words, causal-loop diagrams are a useful approach to describe the relationships and interactions between components of a system. Through the above described analysis, the study identified three leverage points, namely ‘Investment in labor training’, ‘Propensity to share know-how’, and ’Technology adoption on-site’.

A group of four (4) managers from different companies and countries were engaged in building the model. The selected participants came from U.S., Germany, and Japan and worked collaboratively to create a platform for learning, collaborating and decision making for relevant stakeholders. Several follow-up interviews were conducted with the aim at identifying the key leverage points in the system model. The study obtained the mental models articulated by the participants and identified the systemic leverage points related to real-time collaboration in HRB projects. The participating experts used the three identified leverage points to structure and populate a Bayesian Belief Network (BBN) for designing policies on technology implementation which leads us to the next section:

2.3.2. Bayesian belief network

Focus group experts collaborated to establish a Bayesian Belief Network model, using the Causal Loop model as basis. This includes the identification of possible root causes affecting the collaboration in construction projects. The conditional probabilities of a Bayesian belief network are generally assessed from statistical data or by human experts. As a result of incomplete data and partial knowledge of the issue being modeled, the assessment obtained are inevitable inaccurate. In the study, participating experts used the three identified intervention points to structure the Bayesian Belief Network model and to populate the model, they jointly decided the probabilities of how the parent nodes will determine the probability that a child note would be achieved. We asked the following type of questions:

“Given the scenario depicted in model X and a parental configuration Y, what should be the probability distribution over the states of Z?”

This question was asked once for each parental configuration. For example, what are the probabilities that efficient utilisation of digital technology and sufficient knowledge skills of craftsmen will simplify the information flow (See figure 6.1.2). Through this process the stakeholders recognised that their populated Bayesian model indicated that there is under current policy only a 12,3% probability to enhance collaboration and communication of craftsmen (see figure 6.2.2). No sufficient adequate database, recording the past trends of collaboration and communication in the explicit industry was found and the model, therefore, had been populated through knowledge elicited by domain experts with the result that the sheer magnitude formed a considerable cognitive barrier. General knowledge-acquisition constraints as such to generate conditional probabilities set limits on the overall level of accuracy.

A sensitivity analysis of the model indicated that the most effective parameter to enhance collaboration and communication of craftsmen is the possibility to strengthen the ICT focus towards collaboration of craftsmen instead of only focusing on the exchange of information and data.The populated model showed that the probability of enhancing collaboration and communication of craftsmen from 12,3% to 45,6% if factor A is set at 100%. Therefore this policy was determined by the participating experts to be the leverage point for enhancing collaboration and communication of craftsmen in BC projects. By completing the above sequential steps, the Bayesian network model proved to be highly efficient for creating an industry-wide policy with stakeholders' involvement.

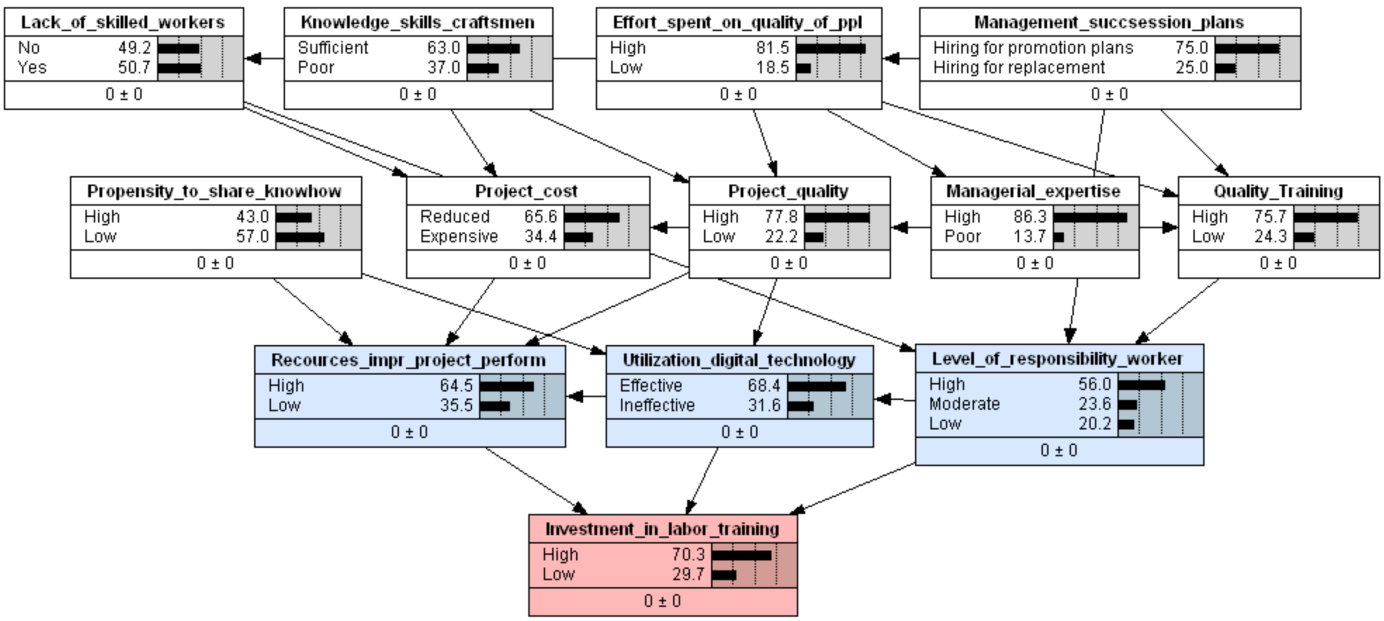


Fig. 11.1.1. Bayesian Belief Network model: Probability analysis of leverage point 1 'Investment in labor training'

☐ Control factors ☐ Identified actions ☐ Goal to be enhanced

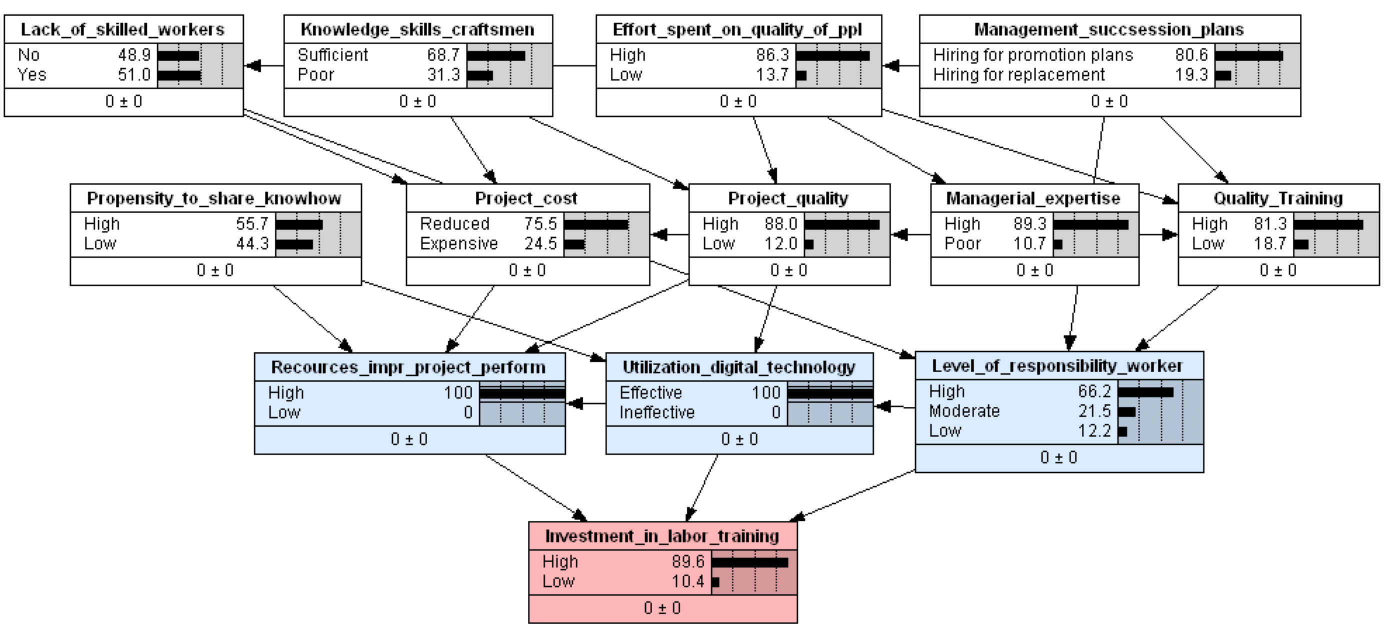


Fig. 11.1.2. Bayesian Belief Network model: Ideal intervention for leverage point 1 'Investment in labor training' (according to experts group *1)

☐ Control factors ☐ Identified actions ☐ Goal to be enhanced

Investment in labor training	Actual value	Est. Value MAX	Increase
Lack of skilled workers	49,2 | 50,7	48,9 | 51,1	0,3
Knowledge of skilled craftsmen	63,0 | 37,0	68,7 | 31,3	5,7
Efforts spent on the quality of people	81,5 | 18,5	86,3 | 13,7	4,8
Management of succession plans	75,0 | 25,0	80,6 | 19,3	5,6
Propensity to sharing know-how	43,0 | 57,0	55,7 | 44,3	12,7
Project cost	65,6 | 34,4	75,5 | 24,5	9,9
Project quality	77,8 | 22,2	88,0 | 12,0	10,2
Managerial expertise (for training)	86,3 | 13,7	89,3 | 10,7	3,0
Quality of labor training	75,7 | 24,3	81,3 | 18,7	5,7
Resources to improve project performance	64,5 | 35,5	100,0 | 0,0	35,5
Utilisation of digital technology	68,4 | 31,6	100,0 | 0,0	31,6
Level of responsibility by each worker	56,0 | 23,6 | 20,2	66,2 | 21,5 | 12,2	10,2
Investment in labor training	**70,3 | 29,7**	**89,6 | 10,4**	**19,3**

Table 6.1. Data of Bayesian Belief Network model shows ‘Investment in labor training

The Bayesian Belief Network (BBN) model was used to determine the actions that influence the leverage point “Propensity to sharing know-how” that could affect the expected outcomes to ensure maximise impact and control. With the model, the group of selected experts analysed the probabilities of how the parent nodes will determine the probability that child nodes would be achieved. Model 1 (Fig. 8.1.) indicates the relation of factors to improve the investment in labor training, one of the three identified leverage points. Strongly associated with project quality and project cost, the resources spent to improve project performance as well as the utilization mechanisms of available technology are major points of action to achieve higher investment in labor training. When determining the probability of a maximal efficient technology usability, the model shows that the level of

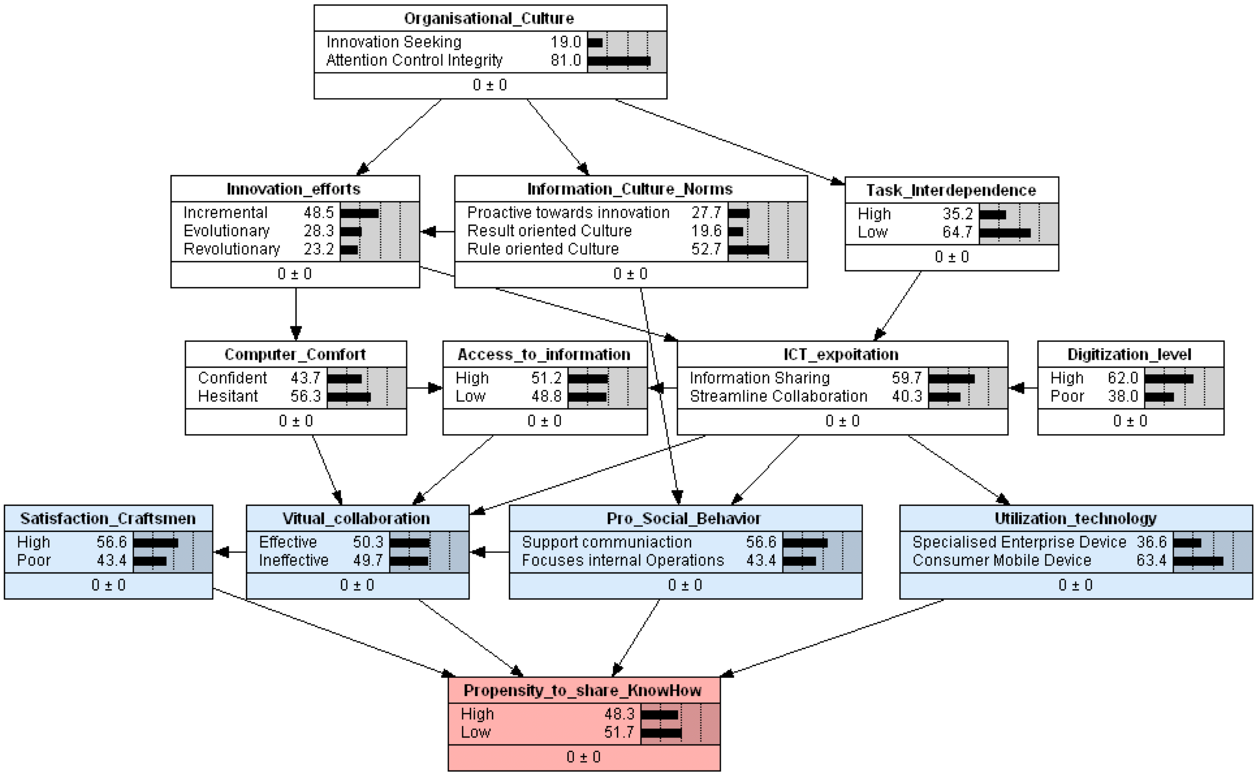


Fig. 11.2.1. Bayesian Belief Network model: Probability analysis of leverage point 1 'Propensity to share knowHow'

☐ Control factors ☐ Identified actions ☐ Goal to be enhanced

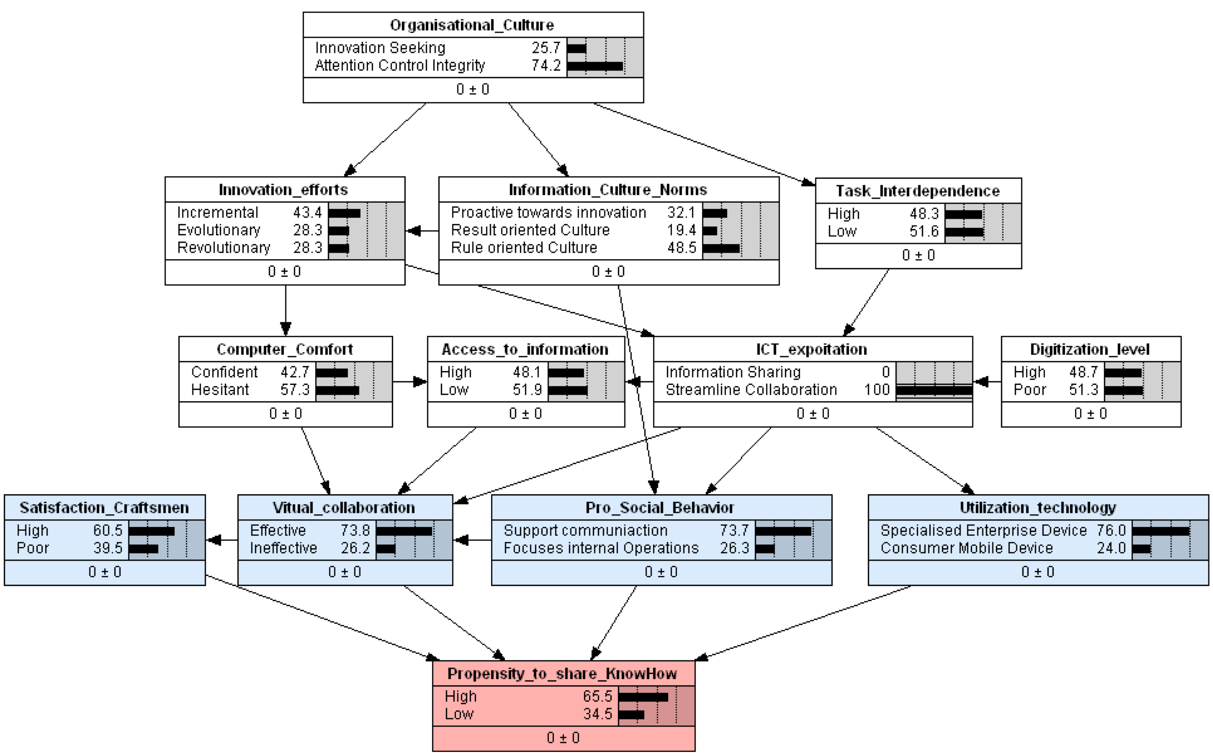


Fig. 11.2.2. Bayesian Belief Network model: Ideal intervention for leverage point 2 'Propensity to share knowHow' (according to experts group *1)

☐ Control factors ☐ Identified actions ☐ Goal to be enhanced

responsibility of workers is strongly affected. This, following back to its parent node suggests to improve managerial expertise in the context of training. According to this probabilistic graphical model, investment in labor training can be increased by 19.3%.

Propensity to share know-how	**Actual value**	**Est. Value MAX**	**Increase**
Oganisation's innovation culture	19,0 | 81,0	25,7 | 74,2	6,7
Innovation efforts	23,2 | 28,3 | 48,5	28,3 | 28,3 | 43,4	5,1
Information culture norms towards Innov.	27,7 | 19,6 | 52,7	32,1 | 19,4 | 48,5	4,4
Workers' task interdependence	35,2 | 64,7	48,3 | 51,6	13,1
Workers' computer comfort	43,7 | 56,3	42,7 | 57,3	-1,0
Workers' access to information	51,2 | 48,8	48,1 | 51,9	-3,1
ICT exploitation towards information sharing	59,7 | 40,3	0,0 | 100,0	-59,7
Project's digitisation level	62,0 | 38,0	48,7 | 51,3	-13,3
Satisfaction od craftsmen	56,6 | 43,3	60,5 | 39,5	13,9
Virtual collaboration	50,3 | 49,7	73,8 | 26,2	23,5
Pro-social behavior towards communication	56,6 | 43,4	73,7 | 26,3	17,1
Utilisation technology towards SE devices	36,6 | 63,4	76,0 | 24,0	39,4
Workers' propensity of sharing know-how	**48,3 | 51,7**	**65,5 | 34,5**	**16,8**

Table 6.2. Data of Bayesian Belief Network model shows nodes (variables) of probability theory

Model 2 (Fig. 8.2.) indicated that the node “ICT exploitation” is the leverage point with the highest probability to improve workers’s propensity to share their know-hoe, knowledge and expertise with within their teams and other companies. The model further suggests, that if companies focus with their ICT exploitation on streamlining collaboration, workers’ pro-social behavior are strongly affected, as well as the nature of technology adoption will thus shift strongly from the major use of consumer mobile devices (Today 63.4%) to the use of specialised enterprise devices. As the model suggests the use of consumer devices would decline up to 24.0% in future projects.

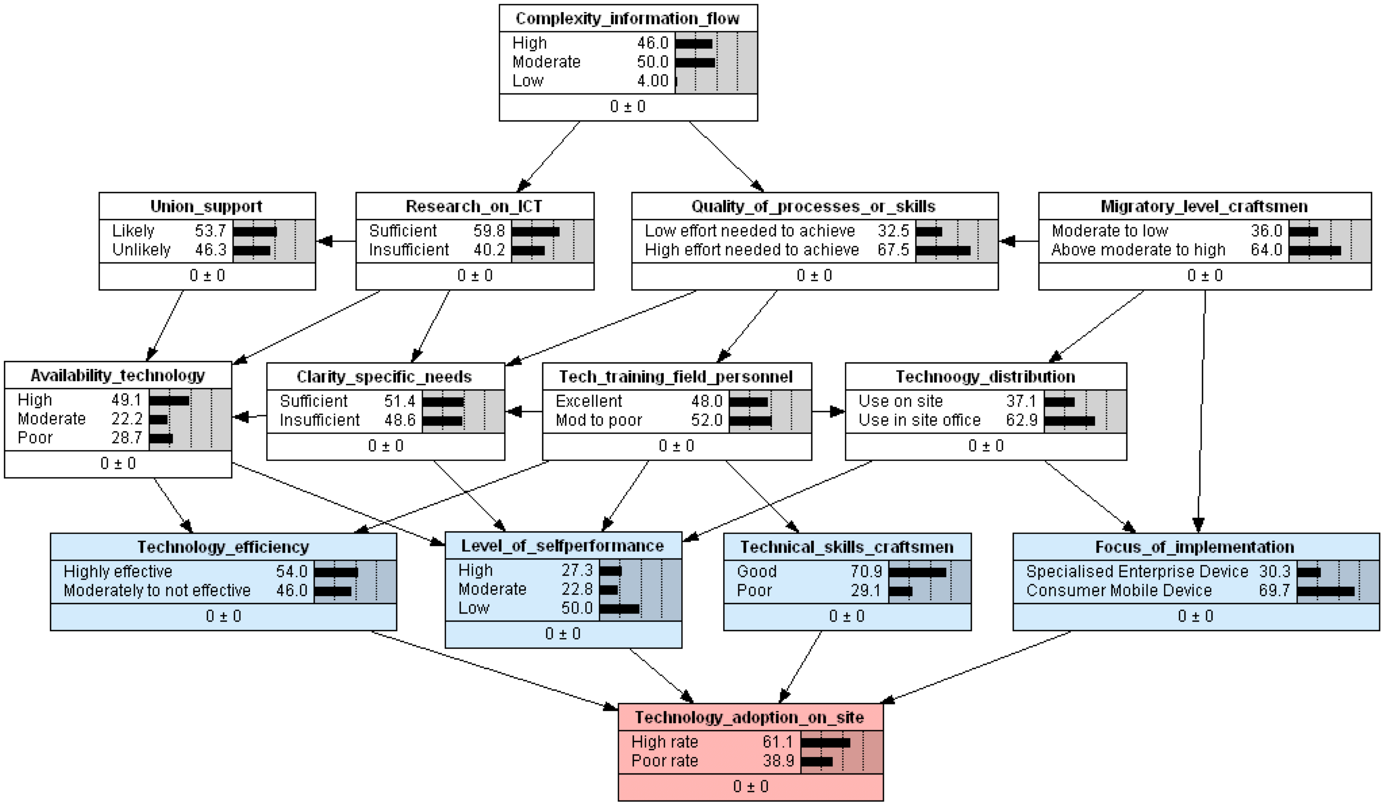


Fig. 11.3.1. Bayesian Belief Network model: Probability analysis of leverage point 3 'Technology adoption on site'

☐ Control factors ☐ Identified actions ☐ Goal to be enhanced

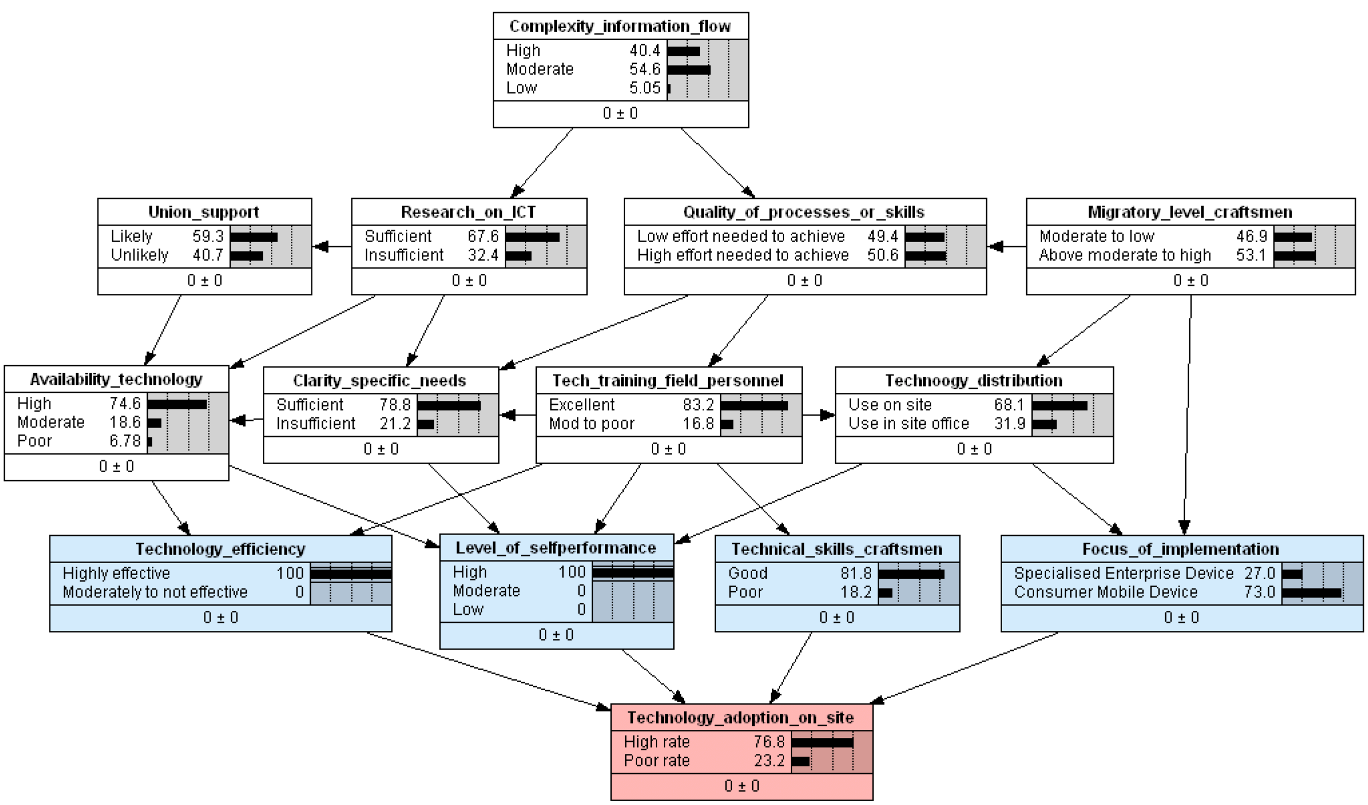


Fig. 11.3.2. Bayesian Belief Network model: Ideal intervention for leverage point 3 'Technology adoption on-site' (according to experts group *1)

☐ Control factors ☐ Identified actions ☐ Goal to be enhanced

As the optimal result the model identified that the current propensity to share know-hoe of construction workers can be increased by up to 16.8% to 65.5%.

Technology adoption rate on-site	**Actual value**	**Est. Value MAX**	**Increase**
Complexity of information flow	46,0 | 50,0 | 4,0	40,4 | 54,6 | 5,1	5,6
Union support	53,7 | 46,3	59,3 | 40,7	5,6
Research related to ICT in construction	59,8 | 40,2	67,6 | 32,4	7,8
Need to achieve quality of processes/ skills	32,5 | 67,5	49,4 | 50,6	16,9
Migratory level of craftsmen	36,0 | 64,0	46,9 | 53,1	10,9
Availability of technology	49,1 | 22,2 | 28,7	74,6 | 18,6 | 6,8	25,5
Clarity of specific needs	51,4 | 48,6	78,8 | 21,2	27,4
Technical training of field personnel	48,0 | 52,0	83,2 | 16,8	35,2
Technology distribution towards on-site	37,1 | 62,9	68,1 | 31,9	31,0
Technology efficiency	54,0 | 46,0	100,0 | 0,0	46,0
Workers' level of self-performance	27,3 | 22,8 | 50,0	100,0 | 0,0 | 0,0	72,7
Workers' technical skills	70,9 | 29,1	81,8 | 18,2	10,9
Implementation focus towards SED	30,3 | 69,7	27,0 | 73,0	-3,3
Technology adoption rate on-site	**61,1 | 38,9**	**76,8 | 23,2**	**15,7**

Table 6.3. Data of Bayesian Belief Network model shows nodes (variables) of probability theory

2.4. Evaluation matrix

	Participant observation	Key informant experts	Self-completion questionnairs
KEQ1 Utilization factor of IT-enhanced tools to communicate with construction personnel on sites	✓	✓	✓
KEQ2 Accessability to project-specific information on sites	✓	✓	✓
KEQ3 Short-term reachability of construction personnel on sites	✓	✓	✓
KEQ4 Importance of communication and collaboration in real-time within and between sub contractors on sites	✓	✓	✓

Table 9. Triangulation matrix of data collection sources

Triangulation was used in order to validate the data through cross verification from three (3) sources. It tested the consistency of findings obtained through different modes of observation and increased the chance to assess some of the factors or causes influencing the results. Four (4) key evaluation questions (KEQ) are listed on the vertical side of the matrix. Three (3) data collection methods are listed on the horizontal side of the matrix.

3. FINDINGS

3.1. Findings from literature review

Hundreds of papers were found on the topics of ICT in construction, very few of them focused on voice-based communication and the improvement of collaboration. No paper was found that focused on Japanese construction in the mentioned context and no paper was found that compared Japan and Western countries on their industrial characteristics. Through analysing the data obtained by screening the papers the findings are the following:

Firstly, a thorough implementation of mobile computing systems into the site environment has failed as of today. Furthermore, current ICT applications are rather non-systematic - since they create either input or output but never both together - and mostly used in the head office or site office rather than on-site. In future projects ICT must be less exploited on storing and sharing information and data but rather in its potential to aid cooperation between people. Before reaching intended recipients, messages communicated today have to go through a long and linear process up - and downstream. The direct communication path , however, must happen between man and man in real-time in the entire construction network.

The most meaningful findings are drawn from the investigated contradiction between the sluggish growth of construction's efficiency and projected requirements of skilled trade workers. With the complexity of building techniques also the technical understanding of trades and crafts will increase, in particular, 78% of large construction companies expect to increase the level of skilled trade workers by 10% or more in the next 10 years. Indicators of productivity, the other side of the coin, show signs of stagnation in construction while 45% of those surveyed expect to increase the amount of self-performed work in the future. The expected ten percent plus increase in construction reminds on the similar development of other industries between 1986 to 1992. By the current state of the research, three preliminary results from interviews and observations have been drawn. To increase overall efficiency and the quality of their projects companies will need to create plans for career growth and retention of their skilled labor. In other words, they must find, train and retain top managers in future to similar plans for those who perform the project work.

Virtually all those polled said they were mindful and supportive in regard of implementing wearable communication technology on the level of field management. All the same, all survey respondents agreed that in future the potential of ICT should be less exploited to store and share data but rather to aid cooperation between people.

3.2. Findings from expert interviews and field observation

Despite all innovative technology ready, construction workers are the most decisive factor to be aware of as a company that aims at implementing new technology into its processes. However, in current strategies, construction workers are barely considered. Recent technology trends are rather utilised to capture and share data as to enhance communication between crafts. Most efforts spent on the supply side support in preference phone applications with the idea that everyone possess a smartphone. This finding applied mainly to Japanese construction but also to the other countries observed. Data from an interview with one of Japan's 'big five', the largest construction organizations in Japan, the data revealed that while downloads on sites were steadily improved over the last years, it was and is the upload of information by workers that has never seen any improvement.

The study found that implementing technology down to the lowest end of construction personnel is strongly connected with the size of the organisation. While larger companies can afford to operate on the bleeding edge, testing the newest features, and often shape standards for technology usage, smaller companies add technologies rather because the clients they are associating with require them to utilise certain levels of technology. Once technology has been proven out in well recognised organisations as something that does improve efficiency or reduce failure it starts to tickle down throughout other companies. Thus, pushing technology for real-time communication down to level of individual craftsman is needed to bridge the various cases in which work tasks are to be laid down. Additional, investment in both training programs and capital infrastructure and a systematic effort by industry, labor, education and governments is needed but unlikely at this time. However, the experts revealed that this would lead to nothing but the next progression in the industry.

3.3. Findings from questionnaire

The questionnaire respondents in this study revealed that the regular utilisation of two-way radios is expected to decrease from currently 19,0% to 6,3% in future projects. This decline of 66.8% indicates the further takeover of consumer mobile devices in voice-based communication in future BC projects. Here it is worthwhile to differentiate between the use of privately owned smartphones and company smartphones: As of today, respondents reported to use mainly their private smartphone on construction sites with 58,4% (Fig. 9). For future projects, however, expectations indicate a trend towards the use of company-owned smartphones with a ratio of 54,3% to 45,7%.

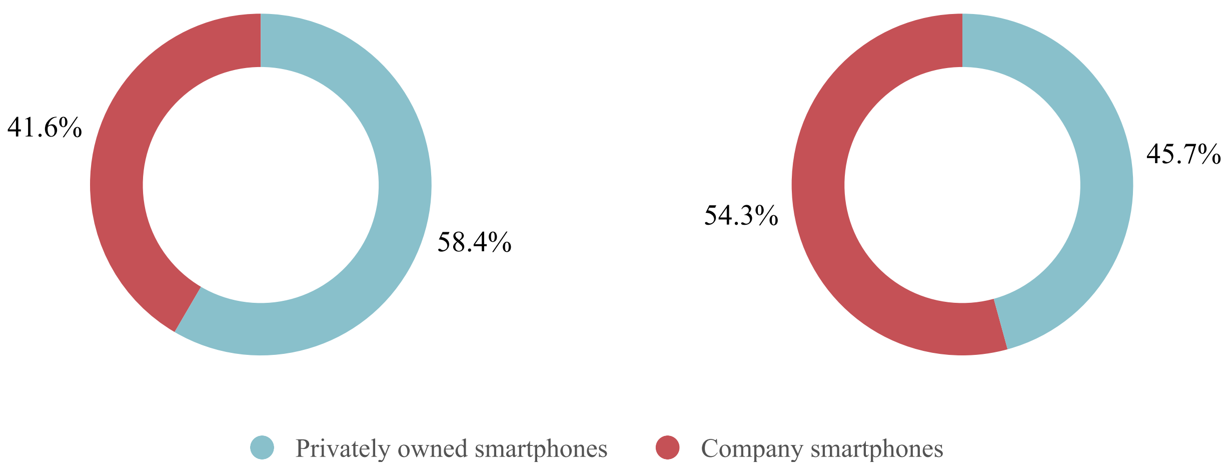


Fig. 12. Usability of smartphones in construction

Contrary to the initial expectations in this study, the use of specialised enterprise tools such as two-way radios or rugged headsets for immediate communication is expected to decline in future project. This trend, underlined by current technology development with a focus on smartphone and pc functions, will on a short term lower the cost for companies and therefore stabilise critical implementation of mobile technology into the level of craftsman. Alarming, however, is the dependency on human factors or, in other words, the willingness of construction workers to use their private devices in an environment they are not designed for. Because of their sensible touch screens, smartphones have one common challenge in comparison with specialised construction tools such as a two-way radio: They require to stop the work task and put off ones glove from the hands to be used.

When respondents were asked on their convenience to reach construction personnel within their company on building sites timely, 25% reported that construction personnel is generally reached at any time and quick. 55% reported that it is strongly associated with their location on sites and not from everywhere personnel can be reached. When asking the same question for personnel of other companies on the same building site, 80% of the respondents indicated that such contact is strongly location dependent and takes usually long time. Other than with personnel within the same company, personnel of other companies can, according to the respondents, not be reached at all.

The average usage-time of internet-based devises on building sites was found to be 3 hours daily and general ICT performance was suggested moderately efficient to very effective. With 100%, all respondents of the survey had invoked collaboration within their team was very or extremely important. 85% claimed the same in regard of collaboration with other teams on the building suite. All of the participants agreed and pointed out that field personnel must be more promoted and trained in order to meet increasing future requirements on their skill levels. 70% of those polled confirmed the earlier observation that enhancing the use of wearable technologies on the level of individual craftsmen can bridge cases in which work tasks are to be laid down due to uncertainties or miscommunications.

Other than initially expected, non of the respondents mentioned to be fully satisfied with the level of access to project-specific information on-site and with almost two third, the majority stated to be merely moderately satisfied. In particular, only 47% of those polled indicated that it is likely to have access to the systems' data when working on building sites. However, with the exception of one respondent, all participants indicated that construction workers need to collaborate more effectively in the next three to ten years when working on-site.

In conclusion of the above findings, the study indicated a misconception of construction workers and managers in regard of the effectiveness of the current ICT use on building sites. While the current level of ICT usage is considered as effective, the majority of respondents claims to be unsatisfied with the level access to get information. Consumer mobile devices such as smartphones or tablets made and continue to making unstoppable inroads into the construction industry in all of the three countries investigated. While being evaluated as a potential alternative to specialised enterprise devises, such as two-way radios, the compromises that consumer devices a la smartphones introduce are often too high to overcome. In section 1.7 is explained that consumer devices have a high failure rate compared to rugged mobile devices (4-8% failure rate of two-way radios; 18-20% failure rate of consumer devices) and thus, the impact of device failure on downtime is substantial. In other words, considering the technical aspects, challenges related to dead spots, network outages, battery performance and audio performance can all contribute to ineffective communication and/or construction workers' downtime. Design elements such as ruggedness and especially the ability to hear clearly in environments with high ambient noise leave the smartphone as a non-suitable device for construction. Listed in table 10. are forty-five (45) factors that were identified to be in direct association with the adaption of mobile communication in building construction environments to improve real-time collaboration on-site.

#	Factors identified	Source
1	Lack of skilled workers	Literature Review
2	Knowledge of skilled trade workers	Literature Review
3	Efforts spent on the quality of people	Expert Interview
4	Management of succession plans	Expert Interview
5	Propensity to sharing know-how	Expert Interview
6	Project cost	Literature Review
7	Project quality	Literature Review
8	Managerial expertise (for. training)	Expert Interview
9	Quality of labor training	Literature Review
10	Resources to improve project performance	Literature Review
11	Utilisation of digital technology	Literature Review
12	Level of responsibility of each worker	Expert Interview
13	**Investment in labor training**	Literature Review
14	Organisations' innovation culture	Literature Review

15	Innovation efforts	Literature Review
16	Information culture norms towards innovation	Literature Review
17	Workers’ task interdependence	Expert Interview
18	Workers' computer comfort	Expert Interview
19	Workers’ access to information	Questionnaire Survey
20	ICT exploitation towards information sharing	Questionnaire Survey
21	Projects’ level of digitalisation	Expert Interview
22	Satisfaction of craftsmen	Expert Interview
23	Virtual collaboration	Expert Interview
24	Pro-social behavior towards communication (workers)	Expert Interview
25	Utilisation technology towards specialized enterprise devices	Literature Review
26	**Workers' propensity of sharing know-how**	Literature Review
27	Complexity of information flow	Literature Review
28	Union support	Expert Interview
29	Research related to ICT in construction	Expert Interview
30	Need to achieve quality of processes and skills	Expert Interview
31	Migratory level of craftsmen	Expert Interview
32	Availability of technology	Expert Interview
33	Clarity of specific needs	Questionnaire Survey
34	Technical training of field personnel	Questionnaire Survey
35	Technology distribution towards on-site usage	Expert Interview
36	Technology efficiency	Expert Interview
37	Workers’ level of self-performance	Literature Review
38	Workers’ technical skills	Questionnaire Survey
39	Implementation focus towards specialized enterprise devises	Literature Review
40	Technology adoption rate on site	Literature Review
41	Sensibility consumer devises	Literature Review
42	Ownership wearable devices	Literature Review
43	Relationship general contractor - sub contractor	Expert Interview
44	Internet access on construction site	Questionnaire Survey
45	Innovation factors construction industry (by country)	Literature Review

Table 8.1. List of identified factors to improve real-time collaboration in HRB construction

3.4. Findings from model and comparison

In this study a BBN was developed to determine the key aspects to consider in adopting mobile communication solutions to aid collaboration in HRB projects. An holistic Causal Loop analysis and BBN probability study, created in a collaborative manner among a group of domain experts, tested and evaluated the opportunities and potential of implementing mobile communication solutions as well as the impact such implementation has on other system elements. The tests concluded improvements of the identified leverage points between 15,7% and 19,3% as seen in table 8.1:

Factors	Goals | Sub-goals		
	Investment in labor training	**Workers' propensity of sharing know-how**	**Technology adoption on-site**
Primary factor identified to achieve the goal	Resources to improve project performance	Choice ICT exploitation focus towards either information sharing or collaboration	Technology efficiency
Secondary factor identified to achieve the goal	Utilisation of digital technology	Choice of utilising technology towards either SED or CMD	Workers' level of self-performance (Trainings required)
Potential to improve by (%)	**19,3**	**16,8**	**15,7**

Table 8.2. Result BBN analysis and potential to increase real-time collaboration in HRB projects

This research revealed that the traditional tools like email, project management software and even the telephone are often one-way communication activities. They lack the real-time collaboration elements necessary for connected engagement, discussion and approval processes. Construction professionals were observed to know and value the importance of working together effectively. The three countries observed indicated various constraints of diverging nature, as seen in the table below:

	 **Germany**	 **Japan**	 **United States**
Most appropriate ICT devise today	 Two-way radio	 Smartphone	 Two-way radio
Most appropriate ICT devise in future	 Smartphone	 Smartphone	 Smartphone
Most appropriate device to enable hands-free approach	 Integrated headset	 Integrated headset	 Integrated headset
Market	Compete mainly on project cost	Compete mainly on technology basis	Compete mainly on project cost
Internet Access	WIFI barely available	WIFI availability eminent	WIFI barely available
Relationship Environment	Dominated by subcontractors	Dominated by view large organisations	Dominated by subcontractors
Innovativeness	Innovative but not attractive	Most attractive and innovative	Moderately innovative but not attractive

Table 8.3. Comparison of three countries observed

It was confirmed that emerging technology can improve real-time in HRB projects. Factors have been identified and categorized. In general, the cellphone makes a remarkable way into construction. Hence, the study observed that consumer mobile devices are too fragile for construction. Construction workers are required to remove their ear protection, their gloves and eventually eye protection to use the device. The touch screen is build very sensible and requires curtain circumstances to function properly. The bottomline is that consumer mobile devices with their high cost, fragile design and inefficient noise clearance are simply not suitable for construction. The following suggestions can be drawn from the comparison of three countries:

In the case of the United States, streamlining collaboration due to special enterprise devices has been found to be the ideal choice. Mobility and real-time communication are key for workers‘ self-performance and specialized enterprise devices ware identified to best satisfy the industry needs in the next years. Advances in two-way radio technology provide better reliability, utility, lower overall costs and above all retain the characteristics of the tools to be manufactured extremely sturdy and durable and thus a convenient product for construction. The weak signal of Wifi on high construction sites make the cellphone a not suitable product. For future projects, however, the study suggests to use headsets to integrate the smartphone into a hands-free environment and enable construction workers to call people without taking the device out of the pocket. Being safely stored inside the pocket, the smartphone becomes a much better suitable device due to its multi functionalism.

Japan’s construction industry was identified to strongly differ in its nature to these of U.S. or Germany. Mobile devices were identified to be the best choice to streamline real-time collaboration. However, to increase efficiency and cost effectiveness headsets are suggested to bridge the sensitivity of mobile devices. In both cases, the headset was seen as the biggest potential to increase the use of both two-way radios and cellphones for real-time collaboration. The three identified leverage points have enabled a clear set of actions to be determined for HRB projects.

4. DISCUSSIONS

The study explored what determines the aquisition and use of mobile communication technology in HRB construction. In this section the findings related to each hypothesis will be discussed:

Hypothesis 1: The study had hypnotized that propensity to share know-how is strongly associated with organizational culture and greater use of mobile communication solutions. The findings in this paper indicate that an open information culture supports workers' willingness to exchange their expertise and knowledge with others involved in the project. However, it was not found whether such an open environment towards instant collaboration would encourage workers that could prefer the structures mechanisms as commonly applied in today's projects. In this study only the direct relation between the innovation culture and workers' propensity could be identified.

Hypothesis 2: As observed in interviews it was believed that implementing mobile communication solutions at the level of individual craftsmen in HRB construction eliminates downtime caused by missing or ambiguous information. This finding could be proven through a questionnaire and further interviews. This finding now however needs to be verified in a feasible implementation test.

Hypothesis 3: As hypotised, labor training is strongly associated with the level of responsibility and task independence of workers. It could be found in the model that the initial assumptions are correct in its context to improve real-time collaboration on the site level. This implies that resources spent on training and promotion is of essence to enhance the level of self-independence. It could not be identified whether there are additional factors that could be contradictory to this finding and thus, more research could improve the model's correctness.

4.1. General suggestions

The need for the integration of more efficient and faster communication processes has been widely acknowledged in the construction industry. Today it can be realistically and feasibly achieved by integrating emerging technology. The paper presented an exploratory observation within the high-rise building construction field and presented factors that can lead to a clearer understanding for stakeholders in the decision making processes.

This study highlighted several emerging views of ICT implementation. First, it provides a model (see Figure 7) for in-depth understanding of the relation and impact of factors that influence ICT implementation during actual implementation of these initiatives. This analysis comprises three key issues. These are: Investment in labor training; propensity to share know-how; and technology adoption on-site.

4.2. Suggestions for construction managers

While ICT, particularly mobile communication devices are commonly known to be powerful and promising in theory, its full potential has by far not been exploited as of today. The study identified that, although technology has the capability to be applied in the whole construction process it has not reached a mature enough stage in BC projects to clearly confirm that it improves work performance entirely in practice. Without motivating construction workers to share their expertise and know-how among team members and inter-related contractors on-site, organisations might fail to take full advantage the information possessed by its workforce.

4.3. Suggestions for technology providers

The study suggested combining systems thinking and design thinking has the potential of improving on the holistic understanding of the current system as stakeholders have the opportunity to view the system from different angles. This has the potential to generate more informed ideas to transform the system with a more holistic view. An approach that combines the two should therefore be more holistic, empathetic and innovative. This said, technology provider can bridge the ambiguous needs of construction companies. Thus, the study suggests to use and further develop the system model as presented in this study and embrace collaboration among the various stakeholders concerned with the implementation of emerging technology.

4.4. Further work

In this paper, a probabilistic graphical model was introduced, that has been developed in collaboration by four (4) respective domain experts. Two of the construction management sector and two of the technology development field. To further improve the models' reliability as an efficient query tool for the construction industry, more experts must collaborate to validate its effectiveness.

Having identified the factors that improve or constrain the planning, implementation and use of effective real-time collaboration solutions, further research needs to focus on transforming these factors and determinants into action plans and integrated strategies that the industry can readily use. This exploratory study has together with selected parties produced the models in Fig. 7 and Fig. 8. The continuous development and population of these models and the development of integrated strategies on industry level should be the focus of the next stages towards implementation of wearable technology in the building site environment. Once an integrated framework has been build, the objective should be to test it in the organizational and project context by general contractors.

Another field of study where to investigate the models' adoptability into other industries such as agriculture, chemical industry, mining or retail. The need of instantly sharing knowledge, skills, and expertise is a common key to successful project performance. Thus, a BBN as introduced in this study could be introduced to other organisations involved in collaborative working practices to improve mechanism and dynamics.

5. CONCLUSIONS

While still inadequately understood in terms of its potential systemic impact and risk, effective real-time collaboration using mobile communication solutions has drawn attention to many researchers in the previous two decades. This paper has described the particular aspects to consider in regard of implementing communication technology in the high-rise building industry. It was identified that a primary reason for cost overruns and delays, most often cited, is poor team communication and collaboration. Mobile Collaboration is an outcome of technology application design focused on mobile devices and people. This emerging market was identified expanding rapidly to include collaboration capabilities such as web and video conferencing.

This research reveales forty five (45) factors to improve real-time collaboration in high-rise construction and suggested integrated actions to be considered in the aspect of communication efficiency. Twenty (20) factors were identified in the literature review; nineteen (19) factors were identified in interviews with domain experts; six (6) factors were identified through the questionnaire survey. Three countries have been observed and the difference between has been concluded. The study identified that emerging mobile communication technology has the capability to not only improve data and information sharing but rather clearly confirms that it improves work performance entirely in practice. Which devices are the most promising is strongly dependent on the country. Japanese construction projects differ from the ones of Germany and United States with the most factor that in Japan every worker has constant access to internet while in the construction in both Germany and U.S. the access to Wifi is a major obstacle. The comparison of the countries has been presented and the decision makers of each country could use the study to study the strengths of one another.

The initial question on how to improve real-time collaboration in HRB construction has been thoroughly discussed and three systemic interventions were introduced. The results of the study as well as future work to be undertaken are described.

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APPENDIX

A. Qualitative Observation - List of Interviewees

Organisation Name	Type	Revenue (USD)	Contact Person	Position
McCarthy Building Companies, Inc.	General Contractor	2.8 bn	Raymond D. LaTour	IT Manager Southern California Region, Los Angeles
McCarthy Building Companies, Inc.	General Contractor	2.8 bn	Rich Henry	President, Northern Pacific Division, San Francisco
McCarthy Building Companies, Inc.	General Contractor	2.8 bn	David Burns	Director Field Systems, San Francisco
Shimizu Corporation, Tokyo	General Contractor	15.0 bn	Yusuke Yamazaki	Manager Technology Division, Tokyo
Webcore Builders, San Francisco	Contractor	1.1 bn	M. Wheeler	Project Manager, San Francisco
Lendlease Corporation, San Francisco	General Contractor	15.0 bn	Anonymous	Specialty trade worker, San Francisco
Lendlease Corporation, San Francisco	General Contractor	15.0 bn	Anonymous	Project Manager, San Francisco
Taisei Corporation, Tokyo	General Contractor	17.6 bn	Aya Onoe	Project Engineer, Tokyo
Taisei Corporation, Tokyo	General Contractor	17.6 bn	Yoichi Tanabe	Senior Manager ICT/BIM
Obayashi Corporation, Tokyo	General Contractor	15.4 bn	Masato Yokozawa	Real Estate Transaction Specialist
Obayashi Corporation, Tokyo	General Contractor	15.4 bn	Tamaki Horii	Deputy General Manager
Hilti Corporation	Construction Tech. Manufacturer	6.51 bn	Heiko Aupperle	Power Tools Senior Designer
Hilti Corporation	Construction Tech. Manufacturer	6.51 bn	Karsten Brandenburg	Senior Product Manager

Table A List of Interviewees

B. Qualitative Observation - List of Field Observations on Construction Sites

Code	Country	Field	Observation subjects
1	Germany	Building Construction Site (Tauberbischofsheim)	Construction Personnel
2	Liechtenstein	Building Construction Site (Schaan)	Construction Personnel
3	Japan	Building Construction Site (Akasaka)	Construction Personnel
4	Japan	Building Construction Site (Yokohama)	Construction Personnel

Table B.1. List of field observations on construction sites

1. Psych. district hospital, Tauberbischofsheim

2. Innovation Center Hilti AG, Schaan

3. Akasaka 1 Chome, Minato ku, Tokyo

1. Commercial 30 story building, Yokohama

Table B.2. Images of field observation locations

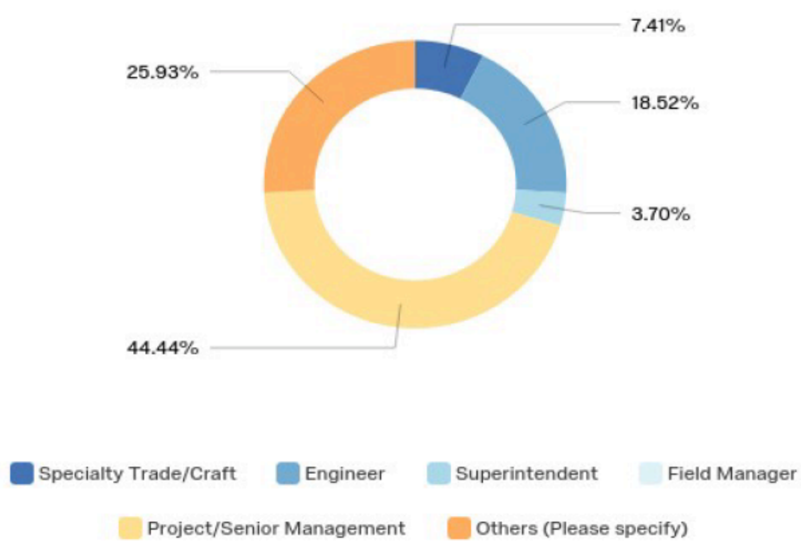
C. Quantitative Observation - Questionnaire Survey

Default Report

Survey on IT-based Communication in BC projects

May 23rd 2017, 3:47 pm KST

Q2 - What is your role in the Construction Organisation?

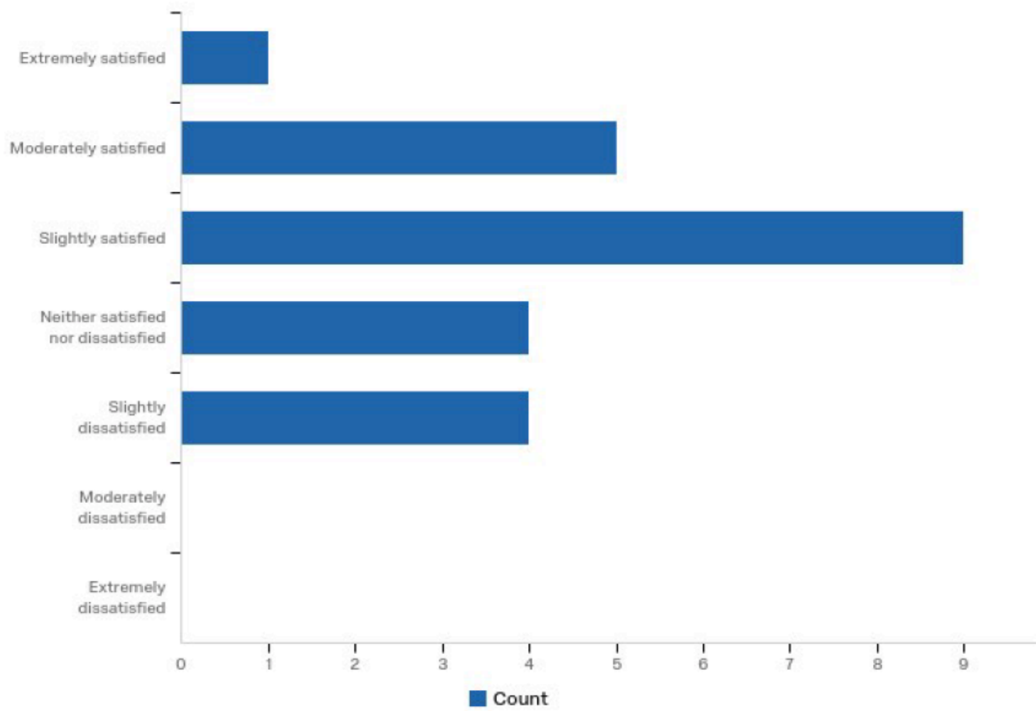


Q2_6_TEXT - Others (Please specify)

Others (Please specify)
IT Field Technology Director
BIM manager, Architectural coordinator
VDC BIM Manager
Director
Research Engineer (@ Institute of technology)
Supporting technical staff
IT Manager

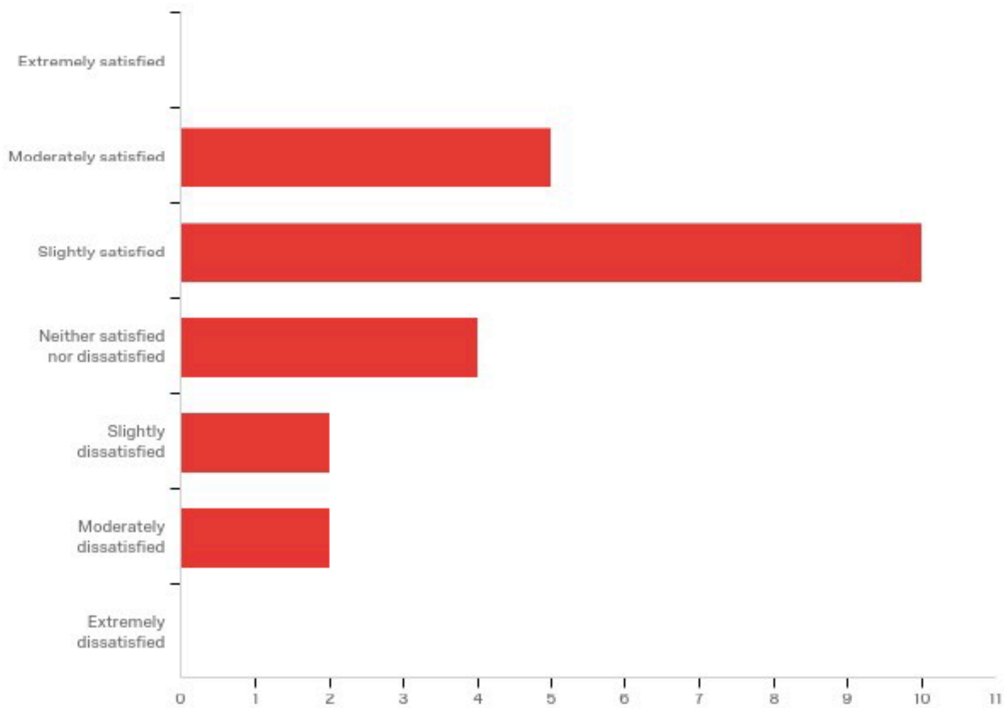
#	Answer	%	Count
1	Specialty Trade/Craft	7.41%	2
2	Engineer	18.52%	5
3	Superintendent	3.70%	1
4	Field Manager	0.00%	0
5	Project/Senior Management	44.44%	12
6	Others (Please specify)	25.93%	7
	Total	100%	27

Q3 - Overall, how satisfied are you with the oral communication among special trade workers on building sites (This includes communication within one company as well as between different companies)?



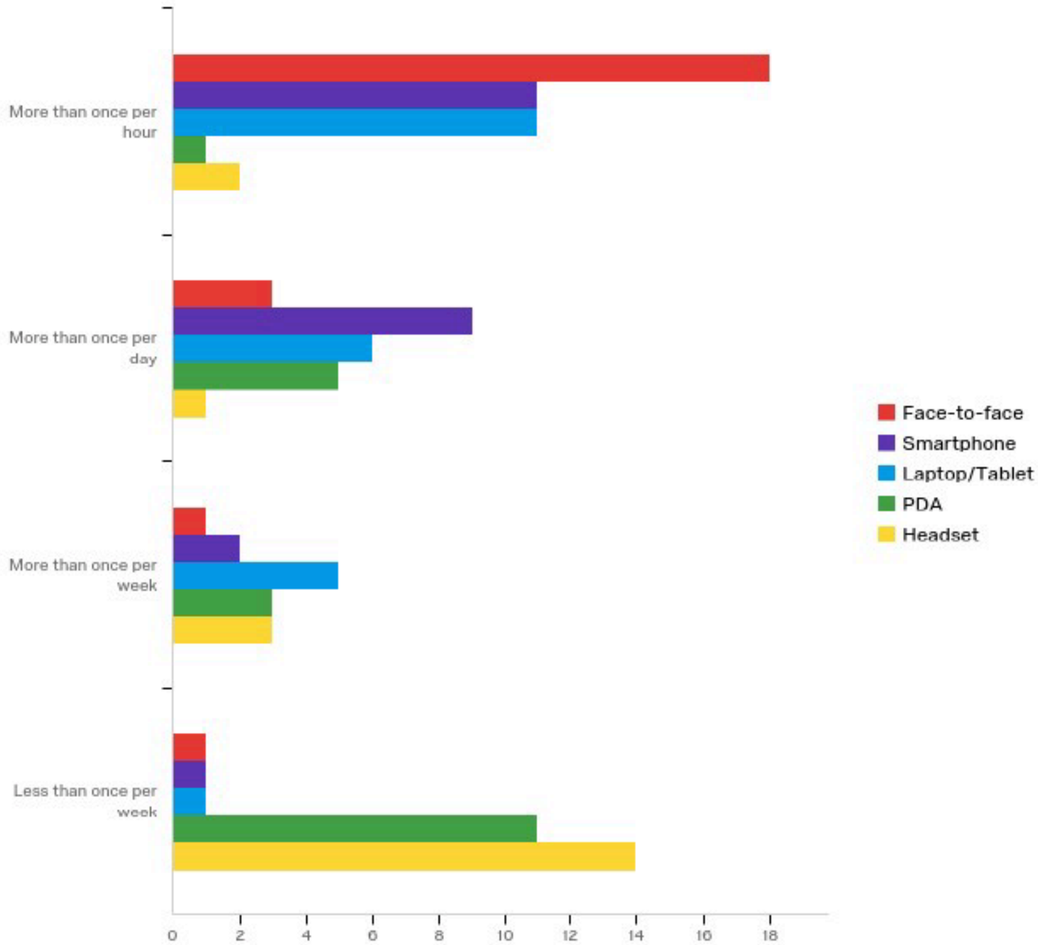
#	Answer	%	Count
1	Extremely satisfied	4.35%	1
2	Moderately satisfied	21.74%	5
3	Slightly satisfied	39.13%	9
4	Neither satisfied nor dissatisfied	17.39%	4
5	Slightly dissatisfied	17.39%	4
6	Moderately dissatisfied	0.00%	0
7	Extremely dissatisfied	0.00%	0
	Total	100%	23

Q4 - Overall, how satisfied are you with the current exploitation of Information and Communication Technology (ICT) on building sites?



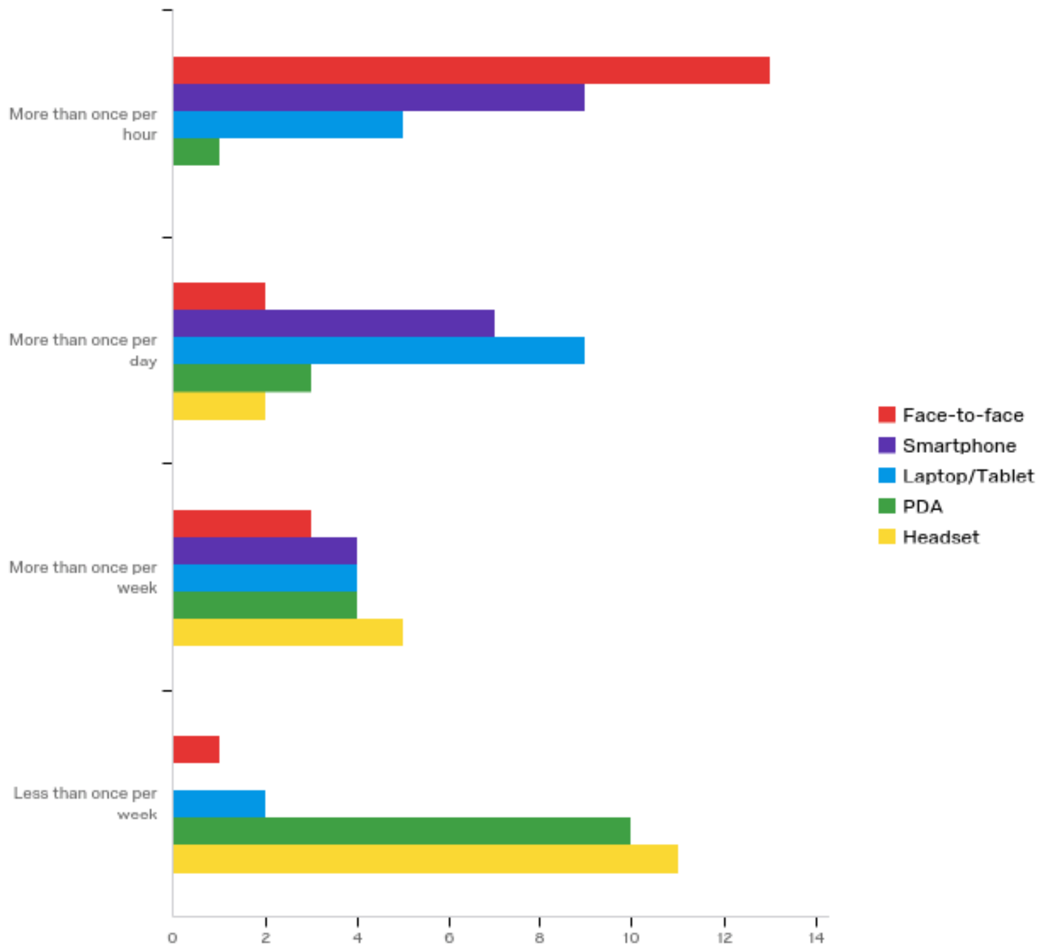
#	Answer	%	Count
1	Extremely satisfied	0.00%	0
2	Moderately satisfied	21.74%	5
3	Slightly satisfied	43.48%	10
4	Neither satisfied nor dissatisfied	17.39%	4
5	Slightly dissatisfied	8.70%	2
6	Moderately dissatisfied	8.70%	2
7	Extremely dissatisfied	0.00%	0
	Total	100%	23

Q5 - In average, how often do you use the following modes/products to communicate with others on-site?
Please check one box in each of the five categories



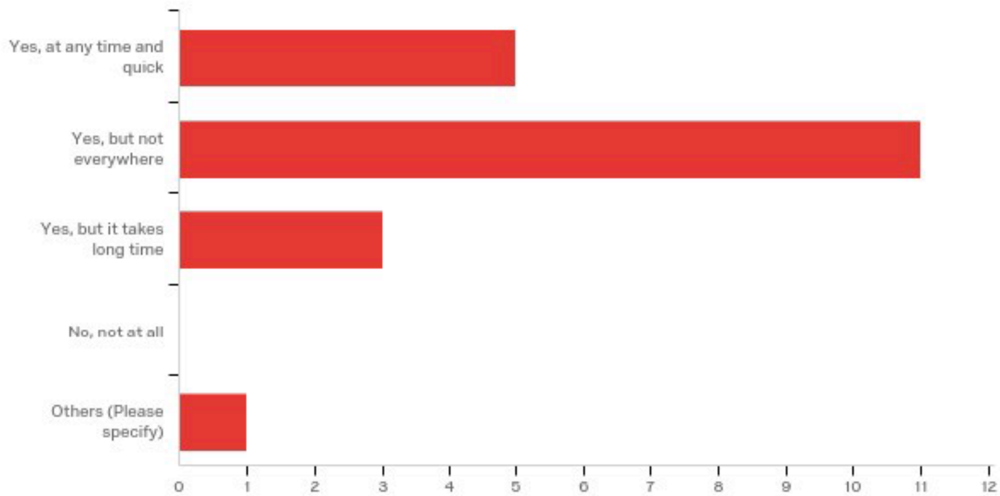
#	Question	More than once per hour		More than once per day		More than once per week		Less than once per week		Total
1	Face-to-face	78.26%	18	13.04%	3	4.35%	1	4.35%	1	23
2	Smartphone	47.83%	11	39.13%	9	8.70%	2	4.35%	1	23
3	Laptop/Tablet	47.83%	11	26.09%	6	21.74%	5	4.35%	1	23
4	PDA	5.00%	1	25.00%	5	15.00%	3	55.00%	11	20
5	Headset	10.00%	2	5.00%	1	15.00%	3	70.00%	14	20

Q6 - In average, how often do you use the following modes/products to share information on-site?
Please check one box in each of the five categories



#	Question	More than once per hour		More than once per day		More than once per week		Less than once per week		Total
1	Face-to-face	68.42%	13	10.53%	2	15.79%	3	5.26%	1	19
2	Smartphone	45.00%	9	35.00%	7	20.00%	4	0.00%	0	20
3	Laptop/Tablet	25.00%	5	45.00%	9	20.00%	4	10.00%	2	20
4	PDA	5.56%	1	16.67%	3	22.22%	4	55.56%	10	18
5	Headset	0.00%	0	11.11%	2	27.78%	5	61.11%	11	18

Q7 - In general, can you reach construction personnel within your company on building sites timely?

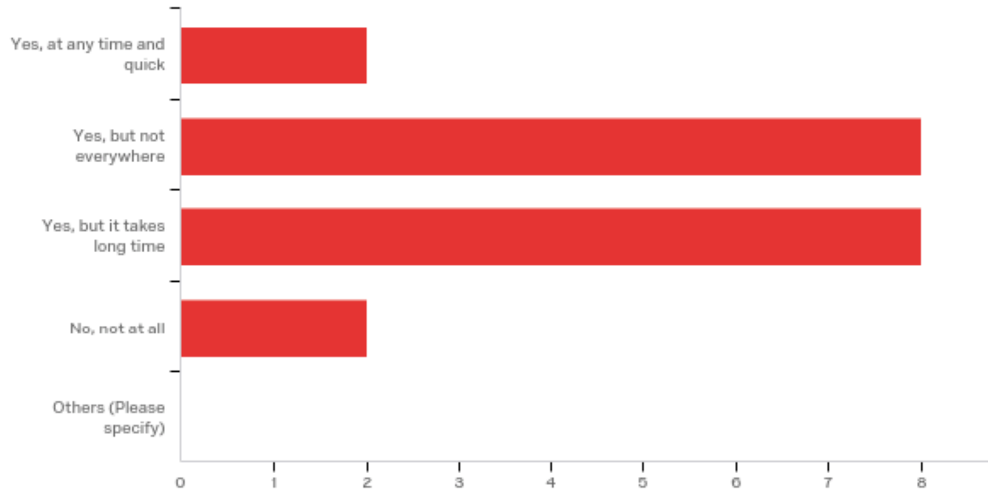


#	Answer	%	Count
1	Yes, at any time and quick	25.00%	5
2	Yes, but not everywhere	55.00%	11
3	Yes, but it takes long time	15.00%	3
4	No, not at all	0.00%	0
5	Others (Please specify)	5.00%	1
	Total	100%	20

Others (Please specify)

Others (Please specify)
yes with radios but not always able to hear them they have to move.

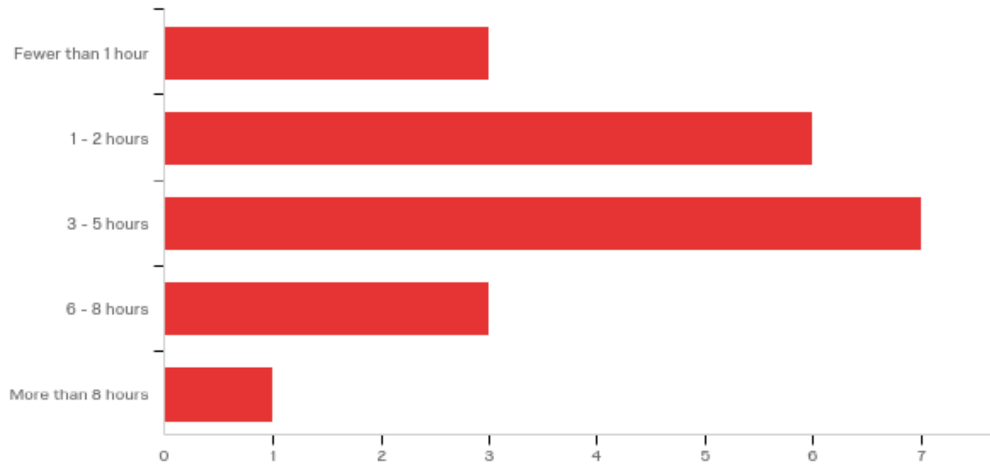
Q8 - In general, can you reach construction personnel of an other company on building sites timely?



#	Answer	%	Count
1	Yes, at any time and quick	10.00%	2
2	Yes, but not everywhere	40.00%	8
3	Yes, but it takes long time	40.00%	8
4	No, not at all	10.00%	2
5	Others (Please specify)	0.00%	0
	Total	100%	20

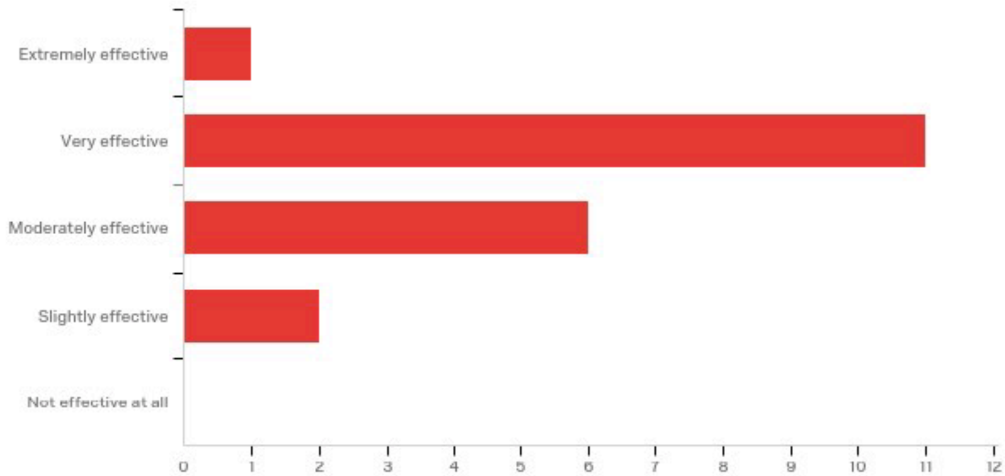
Others (Please specify)
Others (Please specify)

Q9 - In a typical day, how long do you use internet-based devices on building sites?



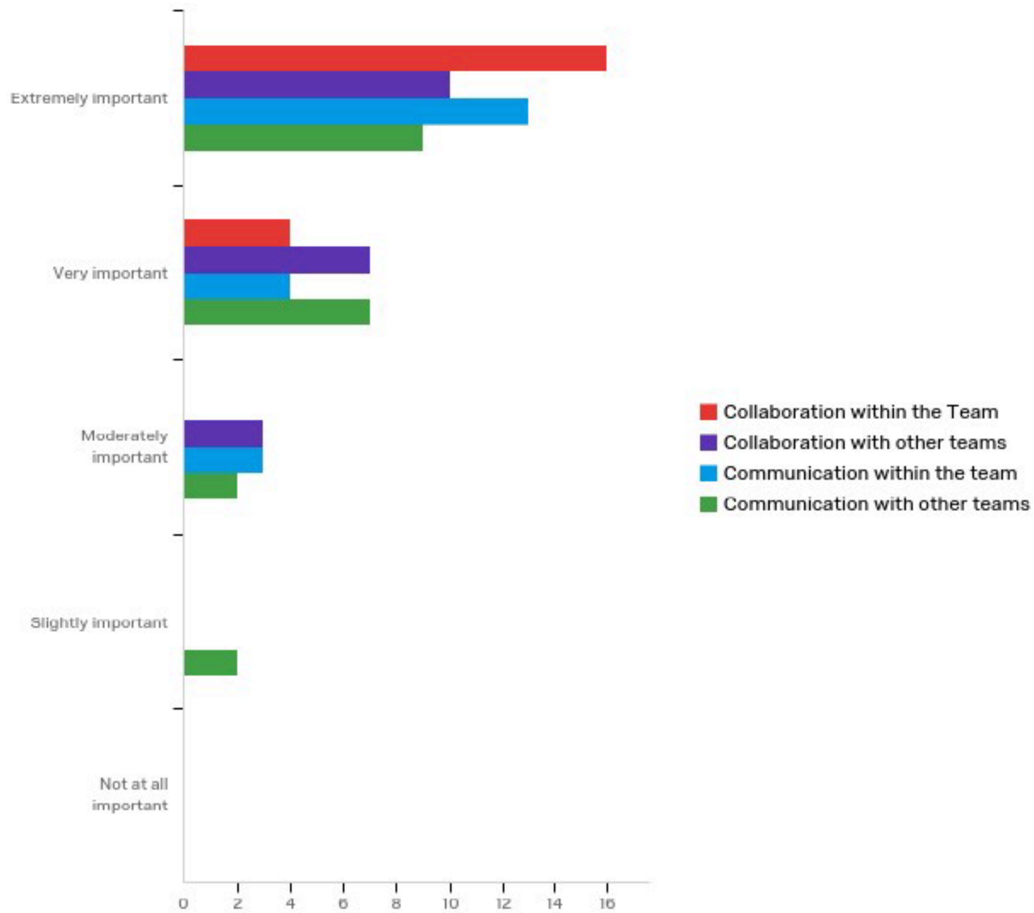
#	Answer	%	Count
1	Fewer than 1 hour	15.00%	3
2	1 - 2 hours	30.00%	6
3	3 - 5 hours	35.00%	7
4	6 - 8 hours	15.00%	3
5	More than 8 hours	5.00%	1
	Total	100%	20

Q10 - Overall, how effective or ineffective is the current use of Information and Communication Technology (ICT) on building sites?



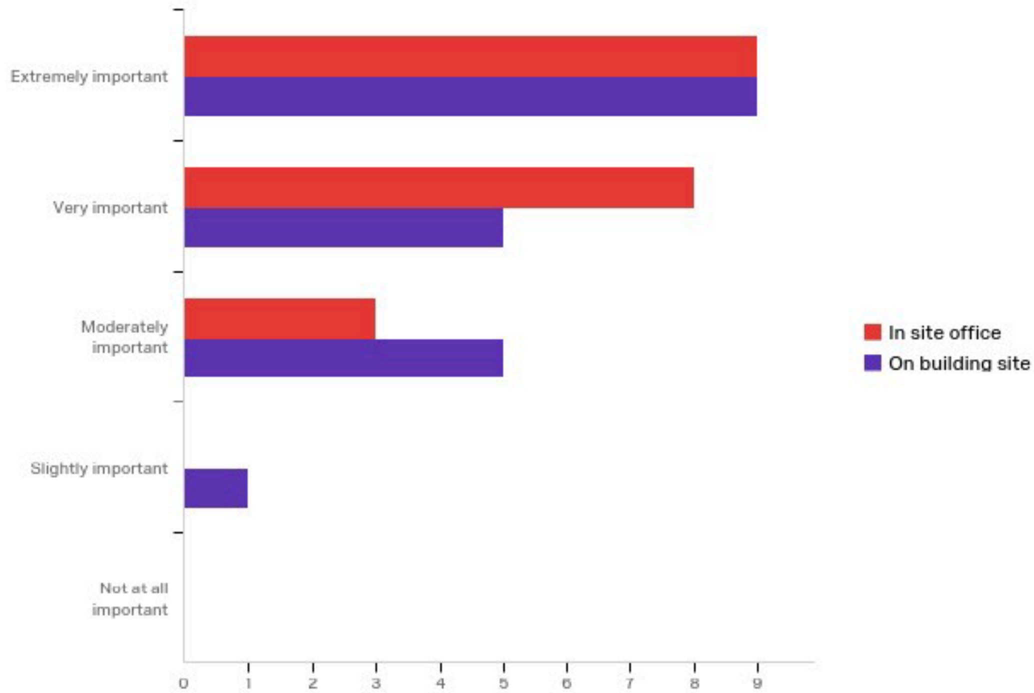
#	Answer	%	Count
1	Extremely effective	5.00%	1
2	Very effective	55.00%	11
3	Moderately effective	30.00%	6
4	Slightly effective	10.00%	2
5	Not effective at all	0.00%	0
	Total	100%	20

Q11 - In general, how important is effective and timely collaboration and communication between sub-contractors in future construction projects?
Please check one box in each of the two categories



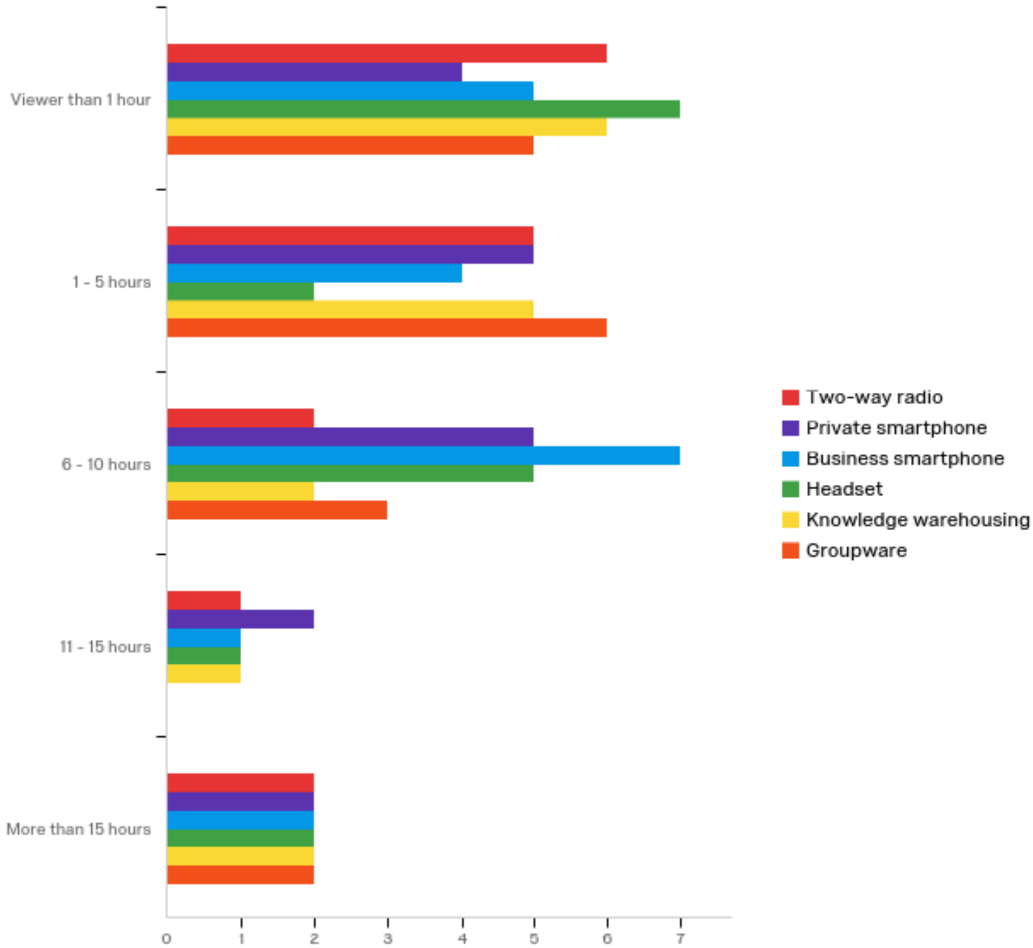
#	Question	Extremely important		Very important		Moderately important		Slightly important		Not at all important		Total
1	Collaboration within the Team	80.00%	16	20.00%	4	0.00%	0	0.00%	0	0.00%	0	20
2	Collaboration with other teams	50.00%	10	35.00%	7	15.00%	3	0.00%	0	0.00%	0	20
3	Communication within the team	65.00%	13	20.00%	4	15.00%	3	0.00%	0	0.00%	0	20
4	Communication with other teams	45.00%	9	35.00%	7	10.00%	2	10.00%	2	0.00%	0	20

Q13 - Overall, how important is effective sharing of pictures and videos in future projects?



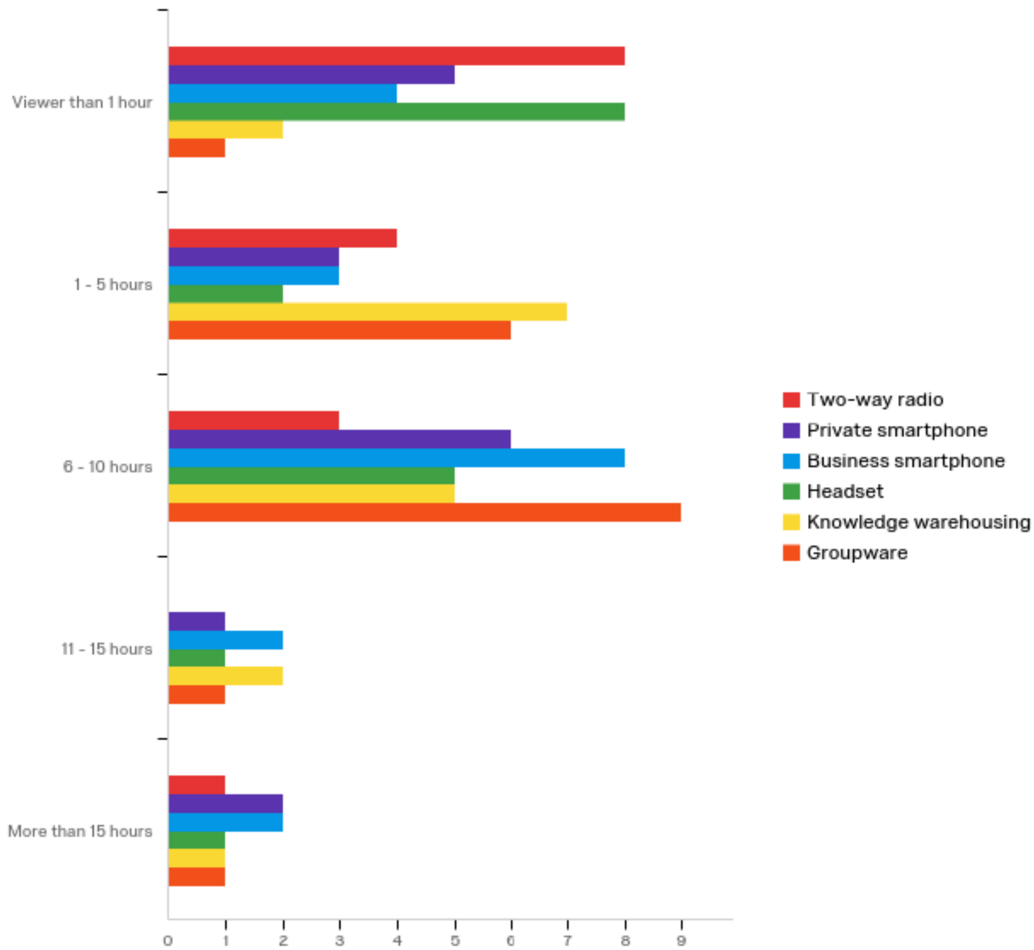
#	Question	Extremely important		Very important		Moderately important		Slightly important		Not at all important		Total
1	In site office	45.00%	9	40.00%	8	15.00%	3	0.00%	0	0.00%	0	20
2	On building site	45.00%	9	25.00%	5	25.00%	5	5.00%	1	0.00%	0	20

Q14 - In current projects on site, how often do you use the following IT-enhanced tools per week (In average)
Please check one box in each of the six categories



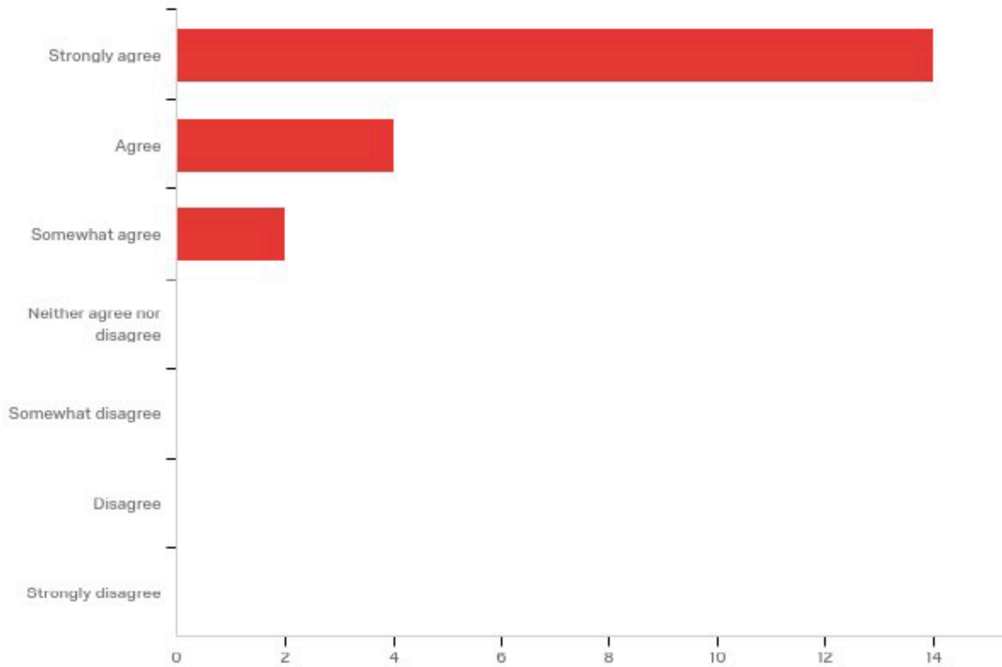
#	Question	Viewer than 1 hour		1 - 5 hours		6 - 10 hours		11 - 15 hours		More than 15 hours		Total
1	Two-way radio	37.50 %	6	31.25%	5	12.50%	2	6.25%	1	12.50%	2	16
2	Private smartphone	22.22 %	4	27.78%	5	27.78%	5	11.11%	2	11.11%	2	18
3	Business smartphone	26.32 %	5	21.05%	4	36.84%	7	5.26%	1	10.53%	2	19
4	Headset	47.06 %	8	11.76%	2	29.41%	5	5.88%	1	5.88%	1	17
5	Knowledge warehousing	11.76 %	2	41.18%	7	29.41%	5	11.76%	2	5.88%	1	17
6	Groupware	5.56%	1	33.33%	6	50.00%	9	5.56%	1	5.56%	1	18

Q15 - In future projects on site, how often are you expecting to use the following IT-enhanced tools per week (In average)
Please check one box in each of the six categories



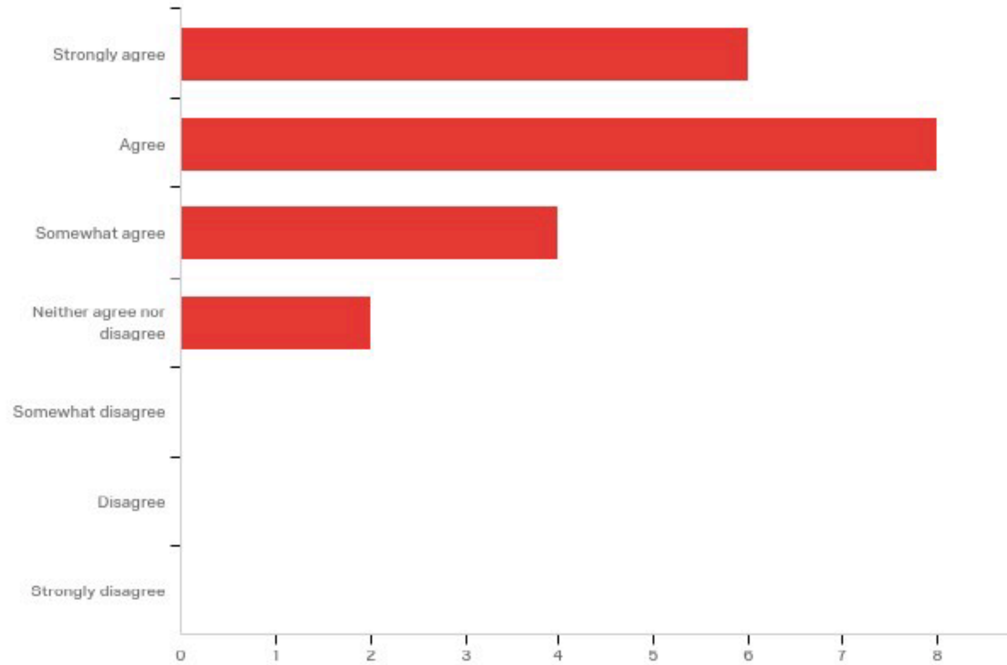
#	Question	Viewer than 1 hour		1 - 5 hours		6 - 10 hours		11 - 15 hours		More than 15 hours		Total
1	Two-way radio	50.00%	8	25.00%	4	18.75%	3	0.00%	0	6.25%	1	16
2	Private smartphone	29.41%	5	17.65%	3	35.29%	6	5.88%	1	11.76%	2	17
3	Business smartphone	21.05%	4	15.79%	3	42.11%	8	10.53%	2	10.53%	2	19
4	Headset	41.18%	7	11.76%	2	29.41%	5	5.88%	1	11.76%	2	17
5	Knowledge warehousing	37.50%	6	31.25%	5	12.50%	2	6.25%	1	12.50%	2	16
6	Groupware	31.25%	5	37.50%	6	18.75%	3	0.00%	0	12.50%	2	16

Q16 - In general, do you agree that filed personnel must be more promoted and trained to meet increasing future requirements on their skill levels?



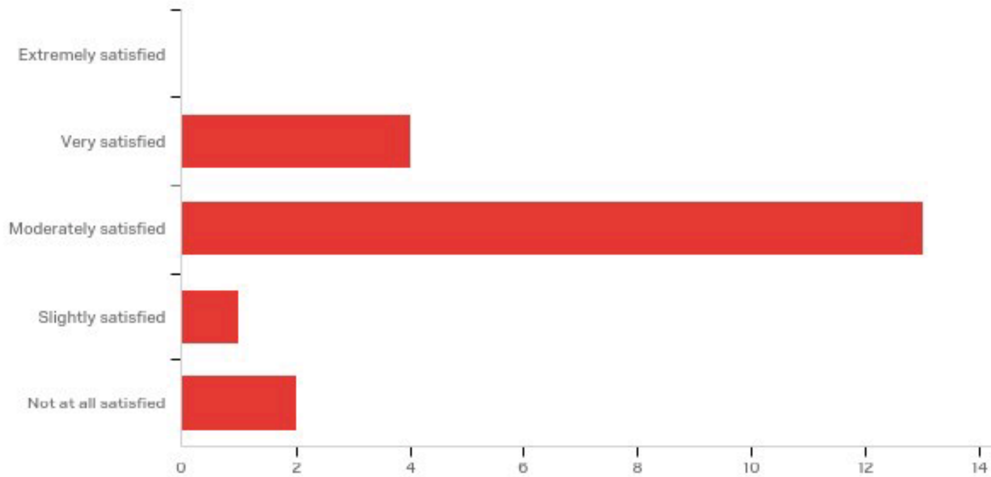
#	Answer	%	Count
1	Strongly agree	70.00%	14
2	Agree	20.00%	4
3	Somewhat agree	10.00%	2
4	Neither agree nor disagree	0.00%	0
5	Somewhat disagree	0.00%	0
6	Disagree	0.00%	0
7	Strongly disagree	0.00%	0
	Total	100%	20

Q17 - In general, do you agree that enhancing the use of wearable technologies (Smartphone, headset, tablet PC, ...) for individual craftsmen can bridge cases in which work tasks are to be laid down due to uncertainties or miscommunications?



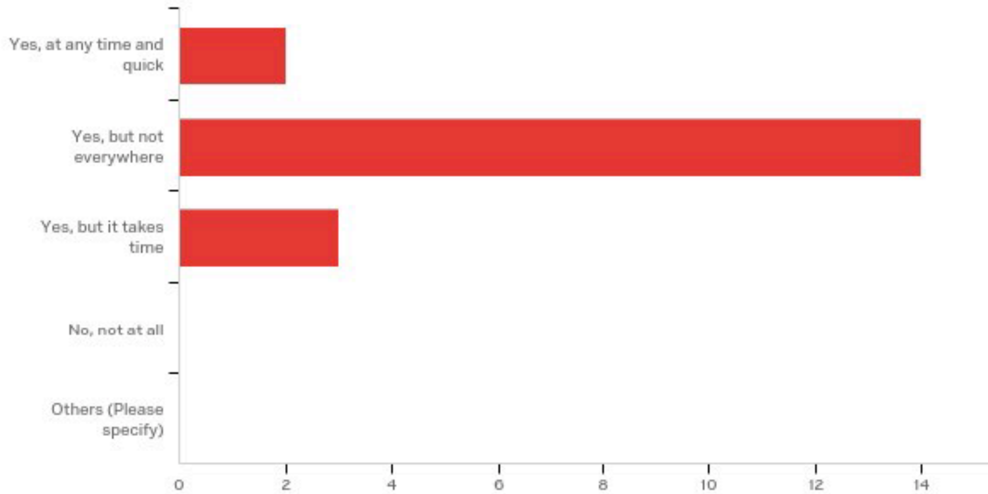
#	Answer	%	Count
1	Strongly agree	30.00%	6
2	Agree	40.00%	8
3	Somewhat agree	20.00%	4
4	Neither agree nor disagree	10.00%	2
5	Somewhat disagree	0.00%	0
6	Disagree	0.00%	0
7	Strongly disagree	0.00%	0
	Total	100%	20

Q18 - Overall, are you satisfied with the level of access to project-specific information on building sites?



#	Answer	%	Count
1	Extremely satisfied	0.00%	0
2	Very satisfied	20.00%	4
3	Moderately satisfied	65.00%	13
4	Slightly satisfied	5.00%	1
5	Not at all satisfied	10.00%	2
	Total	100%	20

Q19 - In general, can you access to project specific information on sites timely?

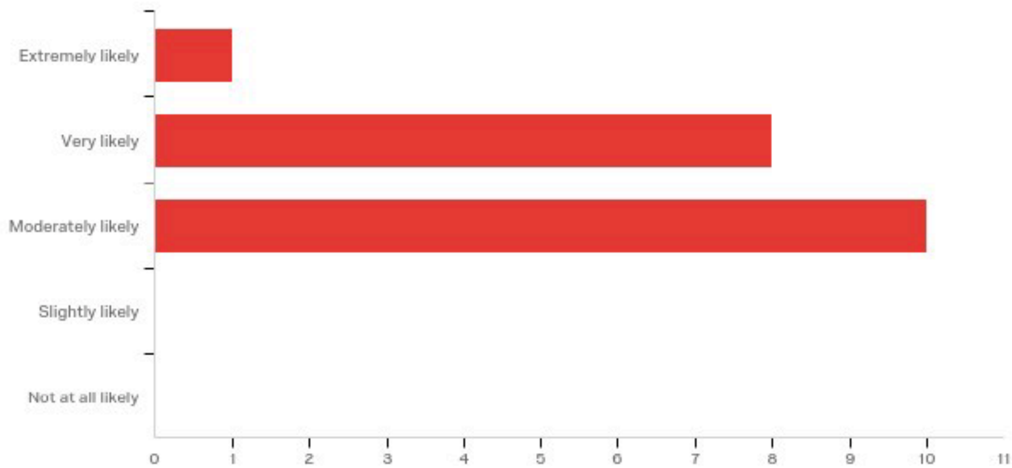


#	Answer	%	Count
1	Yes, at any time and quick	10.53%	2
2	Yes, but not everywhere	73.68%	14
3	Yes, but it takes time	15.79%	3
4	No, not at all	0.00%	0
5	Others (Please specify)	0.00%	0
	Total	100%	19

Others (Please specify)

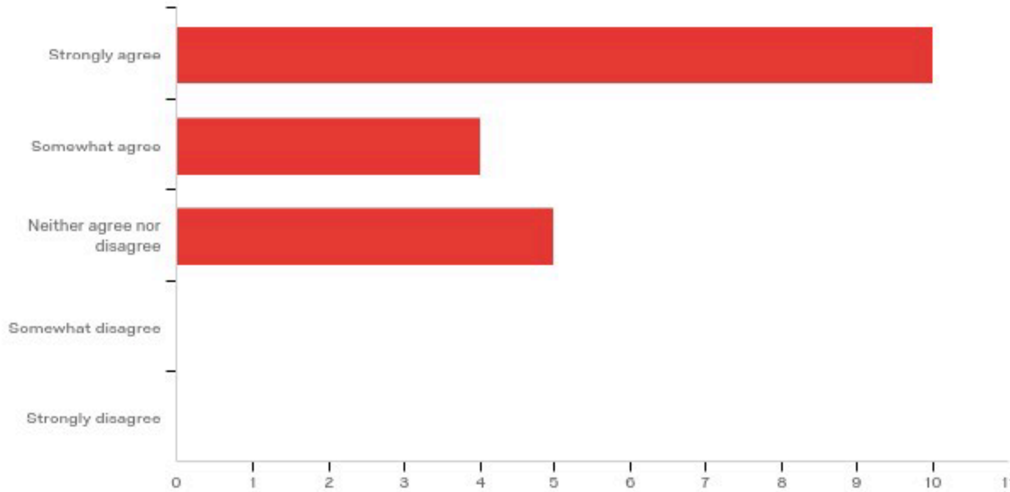
Others (Please specify)

Q20 - In general, how likely is it to have access to the systems' data when working on building sites?



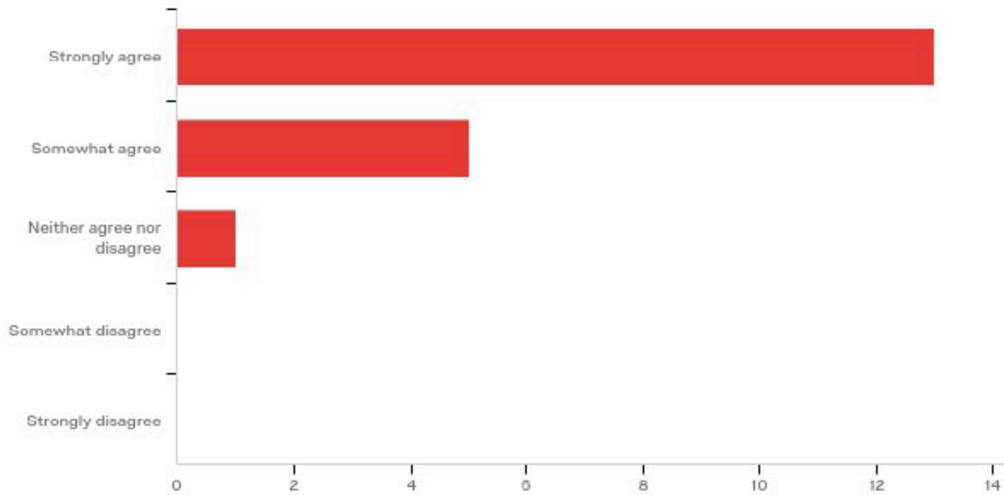
#	Answer	%	Count
1	Extremely likely	5.26%	1
2	Very likely	42.11%	8
3	Moderately likely	52.63%	10
4	Slightly likely	0.00%	0
5	Not at all likely	0.00%	0
	Total	100%	19

Q21 - Do you agree on the statement "Tradeworkers need to access systems' data more effectively the next three to ten years when working on-site" or rather not?



#	Answer	%	Count
5	Strongly disagree	0.00%	0
1	Strongly agree	52.63%	10
4	Somewhat disagree	0.00%	0
2	Somewhat agree	21.05%	4
3	Neither agree nor disagree	26.32%	5
	Total	100%	19

Q22 - Do you agree on the statement "Trade workers need to collaborate and communicate more effectively in the next three to ten years when working on-site" or rather not?



#	Answer	%	Count
1	Strongly agree	68.42%	13
2	Somewhat agree	26.32%	5
3	Neither agree nor disagree	5.26%	1
4	Somewhat disagree	0.00%	0
5	Strongly disagree	0.00%	0
	Total	100%	19

D. System model - List of experts collaborating to develop the CLD and BBN

Organisation Name	Type	Expert Name	Position
McCarthy Building Companies, Inc.	General Contractor	Raymond D. LaTour	IT Manager Southern California Region, Los Angeles
McCarthy Building Companies, Inc.	General Contractor	Rich Henry	President, Northern Pacific Division, San Francisco
Hilti Corporation	Tech. Manufacturer	Heiko Aupperle	Power Tools Senior Designer
Hilti Corporation	Tech. Manufacturer	Karsten Brandenburg	Senior Tool Designer

Table C. List of field observations on construction sites