Integrated Communication, Control and Command of Construction Safety and Quality

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Abstract

Two critical factors that site managers have to control during construction are safety and quality. We envisage that the emergence of Information and Communications Technology (ICT) systems is of great use in effectively promoting safety and quality and exploiting the synergy between these two disciplines. The objectives of this research are to investigate the relationship between safety and quality through the application of ICT. A system of key safety and quality performance indicators was compiled in order to evaluate the potential benefits. Safety and quality leading indicators were recorded prior and after intervention process using a mobile application for communication, control and command of construction of safety and quality (C^4). The results observed in the pilot study showed an improvement of 30% in Quality and reduction of 90% in unsafe activities during the implementation phase. These differences were tested using student t-test and found to be statistically significant at the level of 0.99. Integrated safety and quality leading indicators contribute to enhanced safety and quality and have a potential improvement of up to 90% in construction quality and up to 30% in construction safety. The study contributes to the existing body of knowledge of the high potential of integrated quality and safety leading indicators in construction.

Keywords: Communication, Control, Mobile technology, Quality, Safety.

Introduction

Although construction safety is continuously under the spotlight (Loushine et al. 2006; Wanberg et al. 2013; Zhou et al. 2017; Delgado Camacho et al. 2018; Jebelli et al. 2018) and despite all efforts to enhance safety performance, construction fatalities and injuries continue to be a worldwide plague (Zhang and Fang 2013). The construction industry employs about 6% - 10% of the world's workforce and inspite of continuous effort by researchers and practitioners to improve safety; it is responsible for 30% - 40% of occupational fatalities in many countries across the globe (Guo et al. 2015; Zhou et al. 2015). In the U.S, one out of 100 workers suffered fatal injury due to construction related work accidents resulting in a fatal injury rate of 991 per 100,000 full time equivalent workers per annum workers (BLS 2016), the construction industry in the U.K. is responsible for one third of the workplace related fatalities (HSE 2016). In Israel, according to the Ministry of Economy (IKDRC 2013; MITLDME 2012), the construction sector continues to number the highest death-toll of all other sectors of economy. In 2013 and 2012, construction industry mortality accounted for 50% (IKDRC 2013) and 52% (MITLDME 2012) respectively of the total number of fatalities in all sectors of economy. In addition to the inestimable suffering caused, injuries and fatalities are also associated with considerable financial loss resulting from accompanying disabilities and early retirement (Sawacha et al. 1999; Tuchsen et al. 2009).

Moreover, with the rapid pace of evolution and growth of the construction industry in the 21st century, it is also important to realize the significance of quality to the project success, as project deviations due to quality failures have resulted in large cost overruns and schedule delays (Josephson and Hammarlund 1999). Furthermore, absence of integrated safety and quality management system has resulted in development of local insular ways to maintain control over the project by many organizations causing lack of coordination in information gathering, lack of control, and poor management of the project. An integrated safety and quality management system could be of significant use in reducing the occurrence of injuries and fatalities and facilitating the completion of construction work on schedule and within the allotted budget (Loushine 2006). The literature was reviewed with the aim of identifying features that could enable site managers to improve safety and quality. This survey identified management involvement, effective communication and control during the construction phase as fundamental parameters underlying a safe and qualitative climate in construction. A large qualitative consensus for the importance of the integration between quality and safety management found tin the literature (Wanberg et al. 2013; Love et al. 2015; Love et al. 2016). The study hypothesizes that safe work environment simulates safe work activity and this increases the probability that the task will be accomplished successfully (Husrul et al. 2008).

The advent of smartphones with state-of-the-art of mobile computing technology provides an opportunity to improve the existing situation of on-site construction management (Kim et al. 2013). A comprehensive study conducted by Skibniewski (Skibniewski 2014) shows that more than 130 articles were published from 2006 to 2014 focusing on IT in construction with the effort to provide solution to the construction safety performance. The development of interests of researchers in the application of Information and Communication Technology (ICT) to construction (Lu et al. 2014; Zhou et al. 2013) was followed recently by case and pilot studies of systems. Jiang et al. (2015) explored the potential benefits to construction management of a labor consumption measurement system based on real-time tracking technology on a dam construction site. The technology includes Global Positioning System (GPS), and Geographic Information System (GIS). Accurate analysis of on-site labor consumption is carried out by smart phones with GPS devices, on-site private wireless base stations, and servers. This quantitative labor consumption system improves the effectiveness of site management activities. Edirisinghe and Lingard (2016) researched the potential use of video to communicate safety information to construction workers through smart phones. a method of communicating health and safety information to field-based workers using digital media was developed. Construction managers perceived the system to be beneficial and well received by workers. Han et al. (2017) developed a construction site information gathering and visualization system to help improving the information acquisition capacity of site managers and improve the managerial capacity. Bluetooth Low Energy (BLE) Beacon and Android smart phone device were used for location identification system that locates the equipment and the workers inside the construction site. Field experiment proved the system to be efficient for the acquisition of worker movement information which can’t be acquired before. Site managers can notice accurate details of the construction site and this can contribute to improve the site managerment effectiveness.

This present study investigates the relationship between safety and quality by monitoring safety and quality with the implementation of leading indicators. The study was conducted using development of a mobile application for integrated communication, control and command of construction (C^4) safety and quality. The underlying rationale is that there is a synergy between high safety and high quality performance and vice-versa and that a mobile application for communication and control for these key issues could improve the safety and quality environment of construction sites. The objectives are as follows:

1. To study the synergy between safety and quality in construction using mobile application for integrated control of safety and quality;
2. To examine, measure, and quantify the potential benefits resulting from the implementation of the proposed system in a pilot project;

Literature Review

The next five paragraphs review construction safety, construction quality, safety performance indicators, leading indicators and near miss, and ICT for safety and quality in construction with respect to control and communication at the site and the company level.

Construction Safety

The construction industry is generally considered one of the most dangerous industries worldwide due to its unique, dynamic, complex and decentralized nature (Li et al. 2015). Consequently, safety has always been a significant concern for construction companies. Construction safety appears to be a multifactorial phenomenon gradually related to: culture, contractor organizational parameters, project management, supervision, site conditions, work group, preconstruction services, technology and innovation, and individual characteristics (Khosravi et al. 2014; Karakhan et al. 2018). Choudhry and Fang (2008) interviewed construction workers who had been victims of accidents. Their results demonstrated that management involvement and communication were factors with the most potential to encourage and facilitate site safety. In accordance with this study, Mohamed (2002) concluded that both management commitment and communication are prerequisites to creating and sustaining a positive construction site safety climate. This conclusion was also supported by other studies (Abudayyeh et al. 2006; Jannadi and Bu-Khamsin 2001). Zhang and Fang (2013) calculated that about one third of the hazardous practices responsible for accidents were a result of a deficiency in managerial or supervisory factors. The effective control over subcontractors, was identified by Teo et al. (2004) as a major concern of site managers during the construction phase. This can be attributed to the fact that having a large number of subcontractors increases the probability of poor communication, coordination and control, thereby increasing the likelihood of accidents. Zou et al. (2017) highlighted the research gaps of Building Information Modeling (BIM) based risk management and emphasized the need for multidisciplinary management of construction personnel safety risks. In conclusion, a successful intervention to improve the safety of work conditions on construction sites should focus on stimulating site management involvement, and effective communication and control of safety.

Construction Quality

Ashford (1989) defined the engineering perception of quality as the concept of compliance with a defined requirement, which can be represented by value for money, fitness for purpose or customer satisfaction. Examining the definition of quality used in the literature, Loushine (2006) found that quality could be defined as meeting the expectations of the customer, reduced rework or defects, repeat business and completion on-time and within budget. Rework, a typical indicator of construction quality was defined as the unnecessary effort of redoing a process because of previous mistakes (Love et al. 2015), or of repairing defective products in order to achieve the required performance (Wanberg et al. 2013). Quality deviations and failures, non-conformance and defects are all issues that may require rework (Love 2002).

Quality deviations are a significant expense to the construction industry. Burati et al. (1992) collected data from nine construction projects and identified the direct costs associated with rework, repair and replacement. Their analysis indicated that quality deviations accounted for an average of 12.4% of the total project cost. Love (2002) conducted a questionnaire survey to analyze rework costs in 161 construction projects in Australia and found that rework contributed to 52% of the project cost growth. Although design related issues represent a significant proportion of rework costs, there are often even more rework-related issues during the construction phase (Love and Edwards 2004; Love et al. 2016). Lack of quality management focus, poor communications, as well as poor supervision were identified by Love and Edwards (2004) as major factors contributing to rework. Arditi and Gunaydin (1998) highlighted supervision by contract as well as improved communications and shared information between relevant parties, as factors that could enhance construction quality.

Safety Performance Indicators

Cooper et al. (1991) reported that many of the current safety measurements rely primarily on the incidence of injuries. Two main problems with such measurements is that lost-time injuries are rare events, which makes them unsuitable as the primary indices of the safety program effectiveness, while light injuries, although more frequent, are also unreliable due to under-reporting. Moreover, such methods record only the consequences of the problem and not the cause. Therfore, indicators of safety performance that can be based on direct observation of particular behaviors and activities are more sensitive and reliable (Cooper et al. 1991). In response to these observations, there have been a number of studies that used direct observation and recording of workers' conduct to measure safety performance (Zhang and Fang 2013; Cooper et al. 1991; Komaki et al. 1978; Duff et al. 1994; Choudhry 2014). An additional motivation for this approach is the assumption that the main cause of accidents is reckless behavior by the workers (Sawacha et al. 1999; Nishigaki et al. 1994). In fact, Choudhry et al. (2007) and Blackmon and Gramopadhye (1995) reported that more than 80% of all accidents and injuries could be attributed to hazardous conduct. Direct observations of the workers' conduct with a view to assessing safety, have generally employed one of two alternative methodologies: (1) "all or nothing" (i.e., 100 % safe or 100% unsafe), as reported in (Zhang and Fang 2013; Komaki et al. 1978) or (2) a proportional rating scale (PRS) (Cooper et al. 1991; Duff et al. 1994). The latter assesses the risks of an action, and can measure changes in safety performance.

Leading Indicators and Near Misses

Leading indicators are measurements of construction safety performance introduced in construction safety to predict the future of safety performance. Lagging indicators in contrast are traditional safety metrics which are described by Toellner (2001) as measurements that are associated to aftermath of an accident. Hinze et al. (2013) characterized leading indicators as a set of selected measures that describe the level of effectiveness of the safety process. They examined various safety indicators and conducted a research on 14 projects with over 10,000,000 worker hours focusing on two leading indicators: (1) percent of worker observations that were safe and (2) number of positive reinforcements provided per 200,000 hours. The research demonstrated that indicators are well correlated to the recordable injury rate i.e. measuring safety performance using basic indicators. Additionally, Guo and Yiu (2015) proposed a conceptual framework for developing leading indicators signifying the phenomena for the interest of safety performance in construction.

Nguyen et al. (2016) proposed a generic Bayesian Network model to predict safety, risk of falls from height based on factors influencing safety risk of working at heights and the generic casual relationships among these factors. Considering working using the safety factors (such as pre-planning, operational equipment, and personal protective equipment (PPE)), they examined a case study and concluded that likelihood of falls from height during installation was 0.07% per worker or crew per work hour and likelihood for near miss was 2.62% per worker or crew per work hour. Preplanning is one of the most important safety factors affecting safety performance (Gambatese et al. 2008; Zhang et al. 2013).

Synergy between Safety and Quality

As the synergy between safety and quality is a key issue in developing the methodology of this research, a comprehensive review of the research literature was carried out. Loushine et al. (2006) noted that, despite the difficulties associated with characteristics of the construction industry, there is a general consensus on the subject of possible integration and synergy between safety and quality management. Furthermore, studies by Pheng and Shiua (2000) and Pheng and Pong (2003) confirmed that there are similarities between safety and quality management systems and that the integration of these two systems is a viable method to achieve better co-ordination and utilization of scarce resources. Safety and quality managers apparently agree with the potential benefits of this integration (Pheng and Pong, 2003). Similarly, Hursul et al. (2008) argued that the similarity of safety and quality functions and the fact that they operate simultaneously in the same environment, suggests that it could be beneficial to combine or at least closely coordinate the management activities. A questionnaire survey conducted by Hoonakker et al. (2010) on a sample of general contractors revealed that the implementation of quality management systems in construction also had a potential benefit on safety.

While the aforementioned studies provided positive qualitative evidence for the relationship between quality and safety management, empirical studies are still lacking. Only two recent researches have addressed this relationship empirically, by analyzing safety and quality data resulting from different construction projects. In one case, Wanberg et al. (2013) used data collected from 32 construction projects in the United States to provide the first empirical evidence for a positive relationship between construction safety and quality performance. Their data suggested the following relationships: (1) recordable injury rate can be well correlated with rework and (2) the first-aid rate can be well correlated with the number of defects. In addition, Love et al. (2015; 2016) recently used an exploratory case study approach to analyze the relationship and statistical characteristics of incidents and rework due to non-conformance. The safety and quality data for this study was collected from the database of an Australian contractor over a period of 31 months and revealed a significant association. Notably, 19% of incidents could be attributed to rework.

According to Loushine et al. (2006) the integration of safety and quality management is a possibility, but it requires more significant research before it can be implemented. An empirical study performed by Bernardo et al. (2009) defined integration of safety and quality management system as a multidimensional concept. The multidimensional concept; signifying that nowadays companies which desire greater profitability and better organization implement integrated systems. Their study indicated that 87% of 362 companies implemented an integrated management system. Their aim is reduction of defective products and lost time due to injuries, as well as, improvement of the stakeholders satisfaction and excellence of processes by integration of management systems. A more recent study by Santos et al. (2011) specifies similar advatages of effective integration of safety and quality management systems and its compatibility among different standards. According to literature survey, the application of integrated safety and quality management systems was hypothetical.

ICT for Safety and Quality in Construction

In recent years, the rapid developments in ICT have found wide application in the construction industry. Several studies described below, have revealed the important role played by ICT in supporting improvements in various construction activities, including safety and quality management (Zhou et al. 2013; Skibniewski 2015). Aguilar and Hewage (2013) developed a system for monitoring and management of the construction safety through web based applications and real-time information. The safety data in the system are uploaded by users through electronic devices, wireless high resolution web cameras, wireless sensors and barcodes for automated data submission. This assists the on-site manager in taking informed safety decision on work site by supplying safety indicators related to the specific project. Cheung et al. (2004) developed a web-based safety and health monitoring system for construction projects, using statistical data (number of accidents and working-days lost) and functional parameters (personal protective equipment, safe work practice, electric system safety, etc.). The final output is an executive report which contains key safety instructions, recommendations and graphical presentations. Li et al. (2015) proposed an extension to the behavior-based approach (BBS), termed proactive behavior-based safety (PBBS) to improve construction safety. This method combines traditional BBS management with a form of multiple information technology called proactive construction management system (PCMS), which comprises a real time location and virtual construction simulation systems. The PBBS can automatically monitor and record on-site worker behavior and assign a safety index to quantitatively measure the safety performance. Carbonari et al. (2011) presented a proactive safety management and real-time system based on Ultra Wideband real-time tracking technology, to alert against overhead hazard. The system is designed to trigger warning alerts in order to prevent workers from standing in hazardous positions or from accessing areas with a high possibility of falling objects. Yet another approach, proposed by Park and Kim (2013) involves a novel safety management and safety visualization system (SMVS) that integrates BIM, location tracking, augmented reality (AR) and game technologies. This system has the potential to improve the identification of safety risks. Lin et al. (2014) used ICT tools to improve the efficiency and effectiveness of the safety inspection process with an iPad application designed to reduce inspection process drawbacks and improve day-to-day practices and management of safety inspections. The authors noted that the most noticeable benefits identified in the field evaluation were the reduction of paperwork and faster project safety communication.

A number of studies have revealed that importance of ICT as a tool to promote construction quality. Lam and Ng (2006) presented the use of a web-based quality management for gathering, filtering, managing, assessing and sharing quality data at both project and corporate levels. Kim et al. (2008) proposed a personal digital assistant (PDA) and wireless web-integrated quality inspection and defect management system capable of collecting site defect data in real time and effectively monitoring the status and results of corrective work with all documentation relating to defect management automatically accessible to project participants. Wang (2008) proposed a Radio Frequency Identification (RFID)-based quality management system, which functions as a platform for gathering, filtering, managing, monitoring and sharing quality data. The mobile system developed by Kim et al. (2013) allows users to monitor the construction site, manage construction tasks and share project information in real time. This mobile system could also improve the quality of construction by minimizing rework and defects through appropriate work order and effective information sharing.

Zekavat et al. (2014) noted that advances in information technologies enable users to link critical resources on construction sites to the project website, creating opportunities to improve productivity, safety and quality. Yang et al. (2012) provided empirical evidence that supports the expectation of gaining significant benefits with higher levels of information technology (IT) and application and knowledge management (KM). A structural equation modeling approach was used to validate a model designed to evaluate the relationship between IT applications, KM practice adoption and project success. The findings indicated that use of IT applications positively influences project performance in terms of schedule, cost, quality, and safety via KM practice adoption. Bowden et al. (2006) reviewed the literature for evidence of ICT-related significant improvements in predictability and productivity while reducing construction time and cost, defects, accidents, and waste. The literature review drives the viability and importance of increased technological innovations and use of ICT in construction. In summary, it appears that despite the lack of empirical studies related to construction quality and safety, ICT holds promise as a tool to simultaneously improve the safety and quality performance and to take advantage of the synergy between the two disciplines (Skibniewski 2015; Hwang 2012). As such, the present study hypothesizes that ICT could embrace the integration between safety and quality in construction projects therefore improve safety and quality at the same time.

Research method

The present study was designed to monitor the trend of safety and quality as assessed by safety and quality performance indicators and to examine the interrelationships between construction safety and quality performance resulting from the implementation of an itegrated safety and quality ICT in a pilot study. The study has five phases:

1. Establishment and definition of safety performance indicators;
2. Establishment and definition of quality performance indicators;
3. Development and implementation of the C^4 mobile application in a pilot project to promote both safety and quality;
4. Monitoring and assessment of the safety and quality performance trend during the implementation of the application in the pilot study;
5. Assessment of the synergy between safety and quality benefits accrued following the implementation of the C^4 application.

The C^4 mobile application is used as a tool for enhanced safety and quality. C^4 relies on a mobile cloud-based system to allow users to manage and communicate safety and quality data in the simplest possible fashion by using their smartphones or tablet. The system was developed according to the principles of the relevant Israeli Standards (e.g. 904 (ISI 1998) (formworks for concrete), 118 (ISI 1986) (concrete), 466 (ISI 2003) (concrete structures stability)) and in compliance with the safety regulations of construction operations under the Israel ministry of economy and industry. The aims of the C^4 mobile application are as follows: (1) to create an accessible tool for on-site safety management of construction workers, (2) to reduce the safety control gap between the construction site, mid and upper management levels and (3) to stimulate the continuous improvement of safety and quality through quality performance data accessiblity.

Safety Performance Indicators

The safety performance indicators in this study were defined in terms of workers' behavior because of the literature reports that hazardous conduct is directly related to safety problems. Observations (safety samplings) regarding workers' conduct were recorded weekly at the same time to eliminate the effect of performance time-related variations. At least 400 data points were collected at the site in each safety sampling. The number of data points in the safety sampling determined in order for the safety sampling to be significant at a significance level of 0.95. Forty observations at two minute intervals were recorded for a crew of between ten and twenty form-workers (different for each sampling due to the dynamic nature of the construction site). The number of data points was derived using Eq. (1) :

$$n = \frac{k^2 P(1-P)}{s_\alpha^2} \qquad (1)$$

where, s_α – sampling error, k – the number of standard deviations defining the confidence interval, and p – estimated probability of observing a worker carrying out an activity. If p is estimated at 0.2 the number of observations required is 384. In this study we used a sample of 400 observations.

According to Laufer and Shohet (1991), the fixed interval technique is valid, dependable, considered credible by construction safety experts and is particularly adaptable to the study of short-cycle, highly repetitive group operations. In each round, the observers mark individual behavior according to the following categories: "remarkably safe behavior", "safe behavior", "risks himself", "risks others," and "risks himself and others". Definitions and examples for each of the safety behavior categories are provided in Appendix I. No data was recorded when a worker could not be observed. The summary of 473 observations of safety sampling carried out in week 11 are presented in Appendix II.

At each safety sampling a performance score was generated and the final score was calculated from: Safety Indicator 1 (S.I.1), which represents the quality of safety behaviors and is calculated as shown in Eq. (2).

$$S.I.1 = \sum_{i=1}^{5} P_i \cdot W_i \qquad (2)$$

Where P_i is the percentage of the behavior in each of the five categories, and W_i represents the weight assigned to each category, as follows: (1) remarkably safe behavior, (0.75) safe behavior, (0.5) risks himself, (0.25) risks others and (0) risks himself and others. This weighting system reflects the linear weight of distribution of safety performance and the importance of each category in the total range of safety performance. To illustrate, remarkable safe behavior category is regarded as completed implementation of safety practices and risks himself and others category is classified as ignorance of safety practices. Additionally, safe behavior category is classified as fulfillment of safe behavior and risks others, risks himself categories are classified as dangerous, hazardous behavior. The other contribution to the final score comes from Safety Indicator 2 (S.I.2), which represents the percentage of safe activities. This parameter is calculated from the ratio of safe observations (marked under remarkably safe and safe behavior categories) and the total number of data points collected, as described previously (Zhang and Fang 2013; Komaki et al. 1978). Appendix II illustrates the implementation of 5 categories of safety behavior and 5 categories of respective grading according to the weight of each category for week 11 in the pilot study. The 5 categories define the distribuiton of 473 data points safety behavior of week 11 and safety indicators presented in the table.

Quality Performance Indicators

Although during initial samplings it was noticed that workers were performing a numerous number of reworks, analysis of the project diaries showed an under reporting of the reworks performed (number and/or the related additional cost and hours), hence negating this parameter as a quality indicator in this case study. Furthermore, it became apparent that such a measure of quality is not adequate to monitor the weekly variation of quality performance. This required empirical establishment of suitable quality indicators through direct on site observations.

The quality indicators developed and used in this study is defined by a value between 0 and 100 reflecting the quality state of the reinforced concrete works performed. The parameter was calculated weekly through structured quality samplings and enables the assessment of the overall quality of the construction works.

In-depth investigation of three quality aspects of the performed reinforced concrete works were carried out: (1) concrete works quality, (2) steel works quality and (3) formworks quality. Appendix III depicts the breaking scale for evaluation of quality criteria of steel works, concrete works and formworks. Key quality parameters were measured for each of the categories according to a five point rating scale and the percentage of correct usage recorded. For example, the following parameters were observed for the steel works: adherence to the specifications (through reference to the blueprints), the concrete cover (through measure control and the correct use of the spacers) and the correct installations of the rebars (through the implementation control and the ligature between them). In case of the concrete cover, direct measuring was used to assess the number of times that there was a failure of the concrete cover to meet the requirement (25 mm) and to assign a relative grade on the five point rating scale (where 0% represents complete failure and 100% is completely correct). The final score of the quality indicator. was calculated from the average score of the three categories. This indicator enables the evaluation of the overall construction quality of the reinforced concrete work on a weekly basis. Its cumulative basis assembles the core composites of quality, and thus directs the decision makers regarding quality adherence at all project levels. Safety and quality data was sampled on site during the different stages of implementation of the application. The in-depth investigation is largely designed for concrete works because the pilot study is conducted on a project currently in its structural phase. Quality behavior will further be developed and elaborated in the research focusing on overall construction aspects.

Description of the C^4 mobile application

The C^4 mobile application is designed to provide an innovative solution for the continuous improvement of construction safety and quality by improving measures for control, monitoring and learning as well as implementing all means necessary to ensure safety and quality. A first version of the application was tested in a pilot study designed to examine the applicability of the application. Before workers start to perform a certain activity (work or test), the action, place, time and description of the workers entitled to undertake the task must first be uploaded to the system. Tracing and documentation are carried out in few seconds by scanning the barcode label with a mobile phone or tablet. This scan function allows the user to make all the relevant information, including specific activities, time and place accessible to all levels of the project team. For example, as shown in Fig. 1, the information could include safety specifications, safety and quality checklists, forms, reports, safety risk assessments and safety and quality audits The application enhances users experience thorough an interactive interface in which the user must indicate the completion of surveys, preparedness and hazard surveys, risk assessmentsas shown in Fig. 3. Once the task is completed, the worker (foreman) scans another bar code which automatically executes and delivers the appropriate reports to control centers, managers and decision-makers. The C^4 mobile application proposed in this study permits a simple and effective unified risk assessment and real-time control by observation of workers behavior (such as lack of PPE, lack of safety equipment, etc.) based on location of worker and equipment while minimizing human error and fostering an appreciation of safety risks and construction quality. As presented in Fig.1, the application provides preparedness and hazard assessment (such as check of ladders, stability and suitability of regulations, etc.), survey task reports, safety and quality audits, pre-work risk assessments, safety investigation and quality control. These activities create outcome of reports with recommendations to safety and quality continuous improvement. The combination of technology and methodology represents a method of managing safety and quality while establishing a culture of self-monitoring.

<Fig. 1>

System architecture

C[4] is composed of a mobile application that creates a link between the controlled point, labeled with the aid of tag and cloud system that contains all the knowledge, requirements, regulations, information, history and data required for effective real time control of operational processes. The system is composed of the modules shown in Fig. 2. The main features offered by the application are a customizable database that can be adapted to a specific project along with automatic analysis and synchronization of the data which is made available to all levels of the company. Phase I of the application aims towards structuring and building project model after meticulous analysis of entities such as equipment technical details, workforce, and construction methods. It takes one to two week(s) for successful completion of this stage and largely depends on the technical and design challenges pertaining to a given project. Safety entities such as woerkers identity, workers PPE, and safety equipment are created in the project data base and given all relevant field records. For example: each worker entity is composed of his traingng requirenments and records, each equipment is composed of records of periodical regulatory inspections and licensed required. In the subsequent stage, an automatic synchronization of data-base with the application using hand-held computing devices facilitates multi-user access to entities of the project, while phase III deals with quick-response designation to on-site establishment of formwork, cranes, and PPE. The following phase realizes documentation of safety and quality audit by employing digital checklists in the mobile application. The updated information in prior phase is continuously synchronized to the project and company database in phase V. In phase VI, all the activities and reports presented in Fig .1 are available to all the stakeholders at the project and company level. For example, if a morning site safety and quality suvey was not carried out by the site superintendent, an alert regarding this safety and quality control violation is produced automatically at all levels: site superintendent, construction engineer, construction project manager, director of engineering affaires, etc. Similar alerts are generated in case of failure to complete regulatory safety inspections of mechanichal equipments, or regulatory quality requirement such as structural concrete works quality, etc. The latter fosters the involvement of the stakeholders in quality and safety at the site level in real time mode. Furtherance to the above, the acquired data can be completely integrated into the organizational enterprise resource planning system.

<Fig. 2>

Technical parameters

The main technical parameters of the application are described in Table 1. The system may operate on internet or cellular mediums with transmission rate of 5 seconds providing flexibility and robustness of the application. Bar-code technology is Quick Response (QR) providing reliability and cost-effectiveness. The operating system platform may be applicable for both iOS and Android. The application uses SQL Server, C# and HTML which are beneficial for frequent and secure database access. Get and Post and role-based access control provide robust Application Programming Interface (API) access control mechanism.

<Table. 1>

Effective Control, Command and Communication

The C^4 mobile application makes use of 2D barcode tags, which are physically attached to assets and helmets of the workers. Each tag code is unique to each asset and worker and provides a means of identification in the cloud database. A simple scan of the bar-code by smartphones or tablets provides access to all the relevant information. For example, by scanning the bar-code of an equipment such as tower crane, the user can see the regulatory safety inspections of the tower crane, history of the crane in the project and the required future inspections. The site foreman is responsible for recording worker and task information, including details of personnel and their location. The asset information is automatically stored in the cloud system and transferred (by a simple scan) to a barcode in the task vicinity. Before starting the task, assigned workers are required by the application to use their smartphone or tablet to confirm that they have received the appropriate safety training and have all the necessary personal protective equipment. They also have to check the risks and hazards related to the activity. To stimulate respect for safety issues, supervisors are able to give positive feedback to workers who successfully followed the safety/quality activities or negative feedback to workers who do not observe the safety rules. Personal information is stored in the cloud system and transferred to a barcode attached to the workers' helmet which makes it easier to communicate, control and manage the workforce. Supervisors are required by the application to confirm relevant safety and quality key parameters according to (1) formwork safety and quality (according to Israeli Standard 904 (ISI 1998)), (2) quality of concrete works (according to Israeli Standard 118 (ISI 1986) and 466 (ISI 2003)) and (3) quality of steel works. These criteria appear in the application in the form of a checklist as shown in Fig. 3.

<Fig. 3>

The system facilitates communication between the stakeholders in the project (such as owners, directors, and senior and site engineers as described above) and the use of mobile network technology allows on-site managers to exchange relevant information in real time rather than using classical methods of communication (such as paperwork and meetings). All actions carried out by first and mid line managers are collected and documented and information including safety management regulations, risk assessment, documentation of hazards, safety and quality checklists, training programs, periodical inspections of equipment and manpower, safety events and reports are accessible in real time by site managers, safety officers, members of safety committees and senior company management.

Implementation

The application is used at three levels of the construction company: Level I - construction engineer and directors at senior company level, such as deputy director for operations, Level II - safety manager, contractor and subs and Level III - foreman and crane operator. The application is used for both conducting the safety and quality audits and control by the first line management and at the same time provides control-tool for the mid-line and senior level management. The involvement of the construction engineer and the senior level management plays a pivotal role in the safety and quality control loop.

The application produces 200 daily reports regarding the implementation and fulfillment of safety and quality audits by the first and second line management at the site level and follow-up by company's senior management level. 35 weekly reports are generated covering safety audits, preparedness and continuous improvement procedures.

<Table. 2>

System implementation and monitoring

The phases involved in monitoring the trend of the safety and quality performance resulting from the implementation of the mobile C^4 application were as follows:

1. Base-line phase: This was identified from the initial on-site surveys and represents the starting level of safety and quality performance.
2. Implementation phase: The phase after the base-line phase, during which the C^4 application was working and assimilated on the site. Safety and quality observations were carried out during the implementation phase until the indices converged.

Findings and discussion

This chapter describes the findings from on-site observations performed by the research team over 11 weeks. These observations consist of two weeks of base-line phase and nine weeks of implementation phase. Safety and quality performance observations were recorded in time interval of 1 week according to the categories described in detail in sections 3.1, 3.2 and 5.2.

The average score of the safety indicators during the base-line phase were 61% for S.I.1 and 48.8% for S.I.2 as shown in Fig. 4 which corresponds to an extremely low index of safety. This deficiency was attributed to the limited compliance with the safety regulations by first and mid-line managers. The most frequent hazardous activities detected during this phase were: (1) workers avoided the use of personal protective equipment (2) loads were lifted without a safe harness (3) work was carried out at heights without secure platform (4) workers climbed the formwork and (5) workers threw objects to each other. In addition, there was poor organization of the site layout in terms of crossing safety, fall protection, shaft protection, density, order and organization in general.

<Fig. 4>

Following the implementation of the mobile application, a significant improvement of safety performance over the base-line phase was observed. The convergence of the score of the safety indices was accomplished seven weeks after the beginning of the implementation phase. S.I.1 approached the average score of 80.6% which suggests a qualitative improvement in the workers' safety conduct. Fig. 5 shows the distribution of the worker's safety behavior observed during the sampling performed in the second week (base-line phase) and Fig. 6 shows the distribution relative to the tenth week (implementation phase) when the application had been well assimilated by the first and mid-line managers. The comparison shows a dramatic decrease in unsafe conduct (categories 1, 2 and 3) with the consequent increase of safe behavior (categories 4 and 5) and particularly in the category of remarkable safe behavior (category 5). In fact, S.I.2 approached an average score of 95.3% representing a reduction from 51.1% to 4.8% in unsafe activities/behaviors. Risk due to unsafe activities was reduced dramatically by 90.8% and thus a 90.8% less chance of unsafe activity occurrence. Comparison between the patterns of safety behavior depicts that at the implementation phase the workers adopted fully the conduct of personal safety (as indicated by the 0.2% ratio of category 2 (risks himself) and improved significantly in avoiding risks to others.

<Fig. 5>

<Fig. 6>

The quality indicator score during the base-line phase was 63.8% as shown in Fig. 7. The quality indicator is calculated according to the scales in Appendix III. The score expresses the average of the quality rating for concrete, steel and formworks. The main quality problems detected were: (1) widespread segregations, (2) widespread leakage of concrete, (3) non uniform concrete surfaces, (4) inappropriate concrete cover, (5) lack of adherence of the rebar work to the specifications and design details and (6) formwork support not well performed. These problems were attributed to limited commitment and control of quality issues by the first and mid-line managers. In addition, prior to the implementation phase, a large number of workers were observed to be carrying out reworks. As already described for the safety indicators, the quality indicator improved significantly during the implementation phase reaching the convergence of results after seven weeks of implementation. The score in implementation phase eventually reached an average of 93.5% which represents an improvement of 29.7% as compared to base-line phase in the quality of the reinforced concrete works and reduction of defects in the concrete works, steel works and formworks. Fig. 8 shows the improvement observed in quality of concrete works during the implementation phase compared to the low initial level (base-line phase). Consequently, Fig. 9 displays the improvement observed in quality of steel works among the two phases. In Fig. 9 during base line phase, the concrete cover of the reinforcement bars was around ¾ of an inch (1.70 cm) and the base line quality indicator was 72% and in implementation phase the steel work quality indicator was determined to be 97%. A statistical Student t-test analysis of the safety and quality key performance indicators before and after the implementation of the C^4 application demonstrated significant differences at a level of 99%.

<Fig. 7>

<Fig. 8>

<Fig. 9>

The application is currently being employed in six residential construction sites with an average sq.m. of 42,000 sq,m. during years 2016-2018 in Sivan construction. During this period, the company witnessed one safety incident (injured worker in 2017) and since the beginning of 2018, the company reported no safety and quality incidents. A comprehensive validation study is planned for the next stage of the research.

Conclusions

The objectives of this research were to investigate the relationship between safety and quality using a mobile application for communication, control and command of construction (C^4) safety and quality. The research found a strong potential improvement of safety and quality as a result of integrated implementation of leading indicators through C^4 mobile application. The application is characterized by the following advantages and features:

1. Facilitating structured risk assessment process and establishing control mile-stones for each activity – thereby contributing to minimization of errors in the safety management process;
2. On the job training technology – stimulating the user through an interactive process that validates assimilation, understanding and requires judgment of acceptable risks;
3. Through positive feedback for tasks executed correctly and outstandingly, the technology encourages the understanding of the linkage and synergy between the safety and quality;
4. The involvement of the senior management in safety and quality improved the commitment of senior management to both safety and quality at all levels of the project, the latter improved the safety and quality commitment at the line management of the project;

5. C^4 Technology generates real-time reports of the control variables, facilitating real-time monitoring and remote data analysis at all levels of the organization;
6. Facilitating continuous audits of the safety and quality key performance indicators thereby accelerating the progress of the safety and quality improvement cycles at the project and the company levels;
7. Making the investigation of safety events more effective with the use of documented activities, indicators, reports, training outlines and history of safety events;
8. Creating location oriented control of events, as each event is tagged and can be mapped geographically;
9. Facilitating intra and inter-organizational benchmarking of safety and quality using identical protocols;
10. In the pilot study, reduction of 90.8% in risk due to unsafe activities was observed.
11. The implementation phase indicated very high adherence to the workers' personal safety and significant improvement in the conduct of risk to others.

Indicators for effective automated monitoring of the impact in terms of safety and quality performance during the implementation of the mobile application were developed and implemented in a pilot study. Safety and quality leading indicators were monitored prior to and after the intervention process. It was found that an improvement of 30% in quality indicator, 20% in S.I. 1 and 42% in S.I.2 were accomplished and these differences were found to be statistically significant at level of 0.99. These indicators showed a low level of safety and quality before implementation of the application, which were attributed to limited involvement, communication and control by the first and mid-line managers in safety and quality issues. In addition, lack of control during the implementation of works resulted in poor quality of construction that often required rework. The application of integrated safety and quality indicators stimulated the involvement of company level personnel such as company management, site management and site personnel which enhanced the simultaneous improvement of safety and quality. Improvement was accomplished through generation of daily and weekly reports, risk assessment documentation and recommendation of continuous improvement of safety and quality. This contributed to improvement of 30% in quality and safety as was observed in the pilot study.

The results indicate the synergy between safety and quality. First, statistically highly significant reduction in unsafe behavior and an improvement in the quality of workers safety conduct were observed. The conduct of personal safety behavior was observed to almost fully accomplished (99.8%). Second, the proposed application encouraged the interest of first and mid-line managers in quality aspects.

Quality of construction was improved as a result of reducing the occurrences of defects in concrete works, steel works and formworks. The study provided a clear evidence of effectiveness and benefits of the proposed system by stimulating site management involvement in quality and safety. The study contributes to the existing body of knowledge the high potential of integrated quality and safety leading indicators in construction. Furthermore, it provides a pilot that ICT application can reduce the quality faults in construction in a significant manner. Furthermore, future implementation in larger sample of pilot projects is required in order to validate the results reported in this pilot study.

However, some caveats of the study should be noted. First, the results are influenced by the assistance and motivation provided by the research team during the samplings and implementation of the application. Second, the large benefit observed may be relevant specifically for construction sectors with safety performance similar to that found in Israel and should be examined in similar sectors in Northern America, Asia and Europe. Finally, the proposed system suffers from the following disadvantages: requires time for daily updating of the records; each change of objects in site must be recorded in order to maintain updated safety and quality records and the Geographical Positioning System is not yet sufficiently precise at resolution of the site.

Finally, all the safety and quality performance indicators were taken according to quantitative measurable variables such as rate of usage of PPE, such as helmets, safety boots, gloves, and glasses. The safety and quality performance indicators are the result of hundreds of single samplings for each data point, therefore the potential of human error due to subjective bias is reduced. Nevertheless, these samplings can be automated using visualization system and become fully objective indicators in future research.

Data Availability Statement

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

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Tables

Table 1. Technical parameters of the application

Technical Parameters	C^4 Application
Wireless Medium	Internet and Cellular
Transmission rates (server)	5 Seconds
Bar Code Technology	QR
OS Platform	iOS and Android
Database structure	SQL Server
Application markup languages	C# and HTML
Communication Protocols	Get and Post
API	Role-based access control

Table 2. Implementation parameters of the application

Implementation Parameters	C^4 Application
Company management involved - Level I	1. Construction company staff members (Construction Engineer, Deputy Directors for Operations)
Site management involved - Level II	2. Safety manager who should perform audits regularly, using C^4 application
	3. Contractors & Subs team leaders, who should perform risk assessment prior to every work day or new activity
Site personnel - Level III	4. Foreman who has special and defined duties by the Israeli law
	5. Crane operator who has special and defined duties by Israeli law
Reports	All formal reports and managerial reports were executed using the application. The application made the safety and quality office work totally inoperative, the application automatically produced: ~ 200 Daily reports ~ 35 Weekly reports ~ 200 Safety tour reports ~ 500 crane checks reports ~ Daily updating training logs Tracking dozens overdue in mandatory equipment safety checks and quality audits

APPENDIX I: Definitions and examples of sfety sampling categories

REMAKABLY SAFE ACTIVITIES – Works remarkably safe to himself and to the nearby environment [5]

List of remarkably safe to himself and to the nearby environment:	
1	Ties steel bars with gloves and safety glasses;
2	Work on safe formworks with harness and all other PPE;
3	Carry loads away from others inside the site;
4	Constructs stable temporary structure (scaffolding or formwork) with all necessary PPE;
5	Leaves well protected hole in the floor such as shafts;
6	Maintains fixing device of ladders of scaffoldings;
7	Works bars in safty distance (5-8m.) from others;
8	Welds steel bars with glasses, gloves, long sleeves away from other workers;
9	Lifts safe packed loads with the crane, stay in safety distance, carry loads away from workers and nearby people outside the site;
10	Lifts loads with unsafe tie mechanism.

SAFE ACTIVITIES – Works safely to himself and the nearby environment [4]

List of safe activities:	
1	Works on safe scaffolding;
2	Constructs formworks tied with harness;
3	Welds steel bars with safe welding tool and with gloves and safety glasses;
4	Uses all necessary Personal Protective Equipment PPE (helmets, shoes, glasses etc.);
5	Casts concrete with safe scaffolding platform, and with railings;
6	Cuts steel bars with gloves and safe cutter;
7	Works safely (with PPE) in safe work station (stable, cleaned, without barriers;

8	Lifts safe packed loads with the crane;
9	Lifts loads with safe tie mechanism.

UNSAFE ACTIVITIES – Risks others [3]

List of unsafe activities to others:	
1	Throws tools or materials from high floors;
2	Carries loads above heads of other works inside the site;
3	Carries loads above heads of others outside the site;
4	Constructs or leaves unstable temporary structure (scaffolding or formwork);
5	Leaves open hole in the floor or site;
6	Releases fixing device from a ladder of scaffolding;
7	Dismantles barriers such as railing from lifts shafts;
8	Welds steel bars nearby unprotected workers;
9	Lifts unsafe packed loads with the crane;
10	Lifts loads with unsafe tie mechanism.

UNSAFE ACTIVITIES – Risks himself [2]

List of unsafe activities to the worker:	
1	Does not use helmets;
2	Does not use gloves for manual works;
3	Cuts the bars with the whisk without glasses;
4	Uses the jackhammer without glasses;
5	Lifts loads without a secure harness;
6	throw of objects between workers;
7	Climbs the formworks;
8	Works on the scaffolding without railings;
9	Works without a stable supporting surfaces;

10	Implements formworks in high position without/or with unsafe access platforms;
11	Casts concrete in formworks for walls without safe access platforms.

UNSAFE ACTIVITIES – Risks himself and others [1]

List of unsafe activities to worker and others:	
1	Does not use helmets and carry loads above the head of others;
2	Does not use gloves for manual works and cuts bars with electric device nearby others;
3	Cuts the bars with the whisk without glasses close to others;
4	Uses the jackhammer without glasses nearby others;
5	Lifts loads without a secure harness above heads of others;
6	throws objects between workers, risks others;
7	Works without a stable supporting surfaces above others;
8	Implements formworks in high position without/or unsafe access platforms above other workers;
9	Casts concrete in formworks for walls without safe access platforms above others.

Appendix II: Example of the safety sampling (Week 11)

Category of Safety Behavior				
Risks himself and others	Risks others	Risks himself	Safe behavior	Remarkable safety behavior
1	2	3	4	5
Weight of Safety Behavior				
Risks himself and others	Risks others	Risks himself	Safe behavior	Remarkable safety behavior
0	0.25	0.5	0.75	1
Distribution of Safety Behavior (%)				
Risks himself and others	Risks others	Risks himself	Safe behavior	Remarkable safe behavior
0.21	0	4.86	68.08	26.85
Safety Performance Indicators				
S.I.1 (%)		S.I.2 (%)		
80.34		94.93		

Rate of the formworkers team using helmets?				
1	2	3	4	5
Less then 20 %	20-40 %	40-60 %	60-80 %	80-100 %
Rate of the formworkers team using safety boots?				
1	2	3	4	5
Less then 20 %	20-40 %	40-60 %	60-80 %	80-100 %

Is there in the site unsafe equipment (expose electricity device, lift not maintained, unsafe scaffolding, unsafe ladders)?
Specify : No

How is the level of the site layput organization in terms of the safety of crossing, protection off falls, protection shaft, density, order and organization in general ?				
1	2	3	4	5
Less than 20%	**20-40 %**	**40-60 %**	**60-80 %**	**80-100 %**
Most of the site is unsafe condition, no handrail mounted, unsafe scaffolding, most of the equipment and materials (80%) are in disorder.		Part (50%) of the equipment in a safe, smooth and safe passages are missing hedge details.		The majority of materials and equipment in safe, safe passages, railings and fencing under the regulations

Appendix III: Quality performance indicators (reinforced concrete works)

Quality Performance Indicators					
Concrete Works					
Criteria	Grade of Quality				
	Extremely widespread in the concrete works	Widespread in most of the concrete works	Moderately widespread	Not present in most of the concrete works	Completely absent in the concrete works
	0%	25%	50%	75%	100%
Segregation	0%	25%	50%	75%	100%
Shrinkage cracking	0%	25%	50%	75%	100%
Surface not uniform	0%	25%	50%	75%	100%
Leakage of concrete between junctions	0%	25%	50%	75%	100%
Steel Works					
Criteria	Grade of Quality				
	Extremely not correct in all cases	Not correct in most of the cases	Moderately correct	Correct in most of the cases	Completely correct in all cases
	0%	25%	50%	75%	100%
Concrete Cover correct use of spacers	0%	25%	50%	75%	100%
Ligature of the bars	0%	25%	50%	75%	100%
Adherence to specification and design details	0%	25%	50%	75%	100%
Formworks					
Criteria	Grade of Quality				
	Extremely not correct in all cases	Not correct in most of the cases	Moderately correct	Correct in most of the cases	Completely correct in all cases
	0%	25%	50%	75%	100%
Accuracy of formwork verticality and horizontality	0%	25%	50%	75%	100%
Support well performed (groundplate, props.)	0%	25%	50%	75%	100%
Deformation of the surfaces	0%	25%	50%	75%	100%

Fig. 1. Activities, reports and outcomes of the C4 mobile application

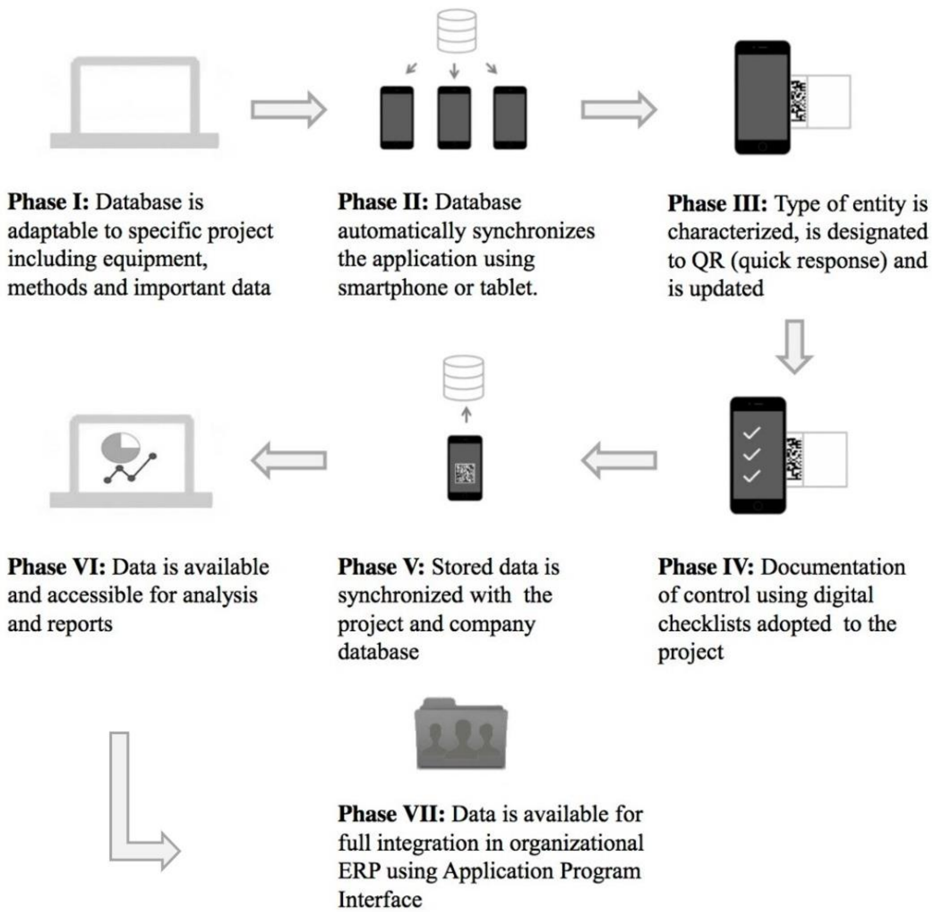

Fig. 2. C^4 System architecture

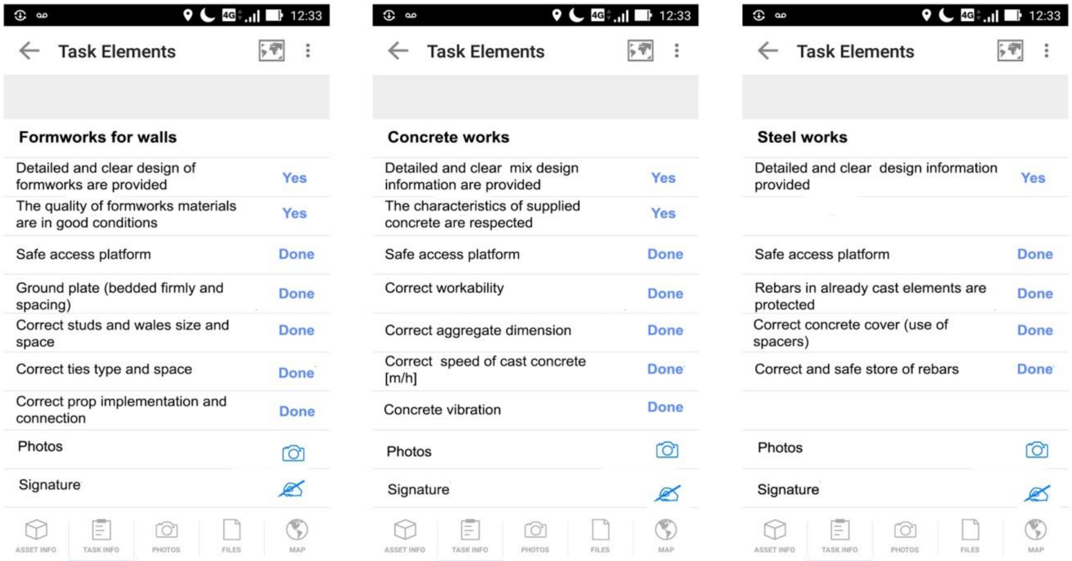

Fig. 3. Screenshots of some of the C^4 safety and quality parameters

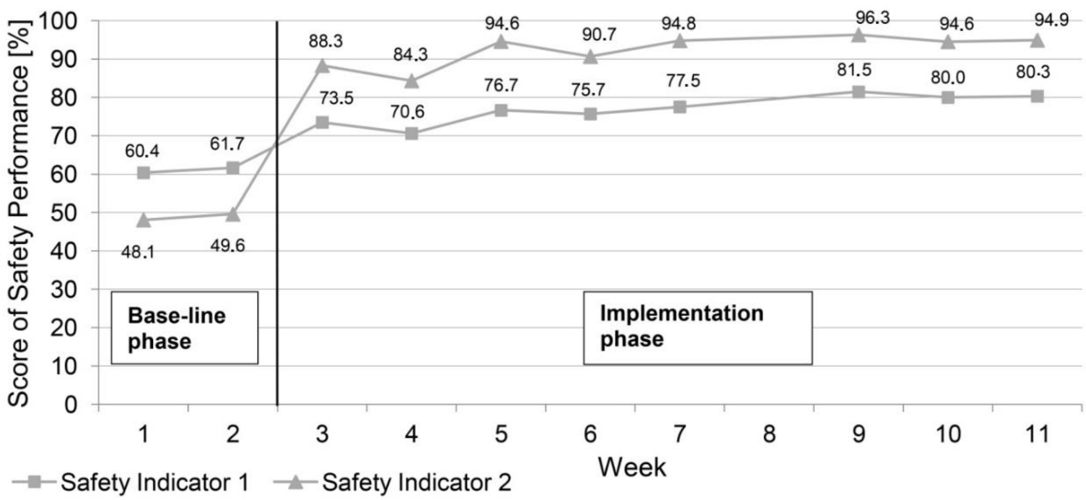

Fig. 4. Trend of weekly safety performance during the phases of implementation of the C4 application

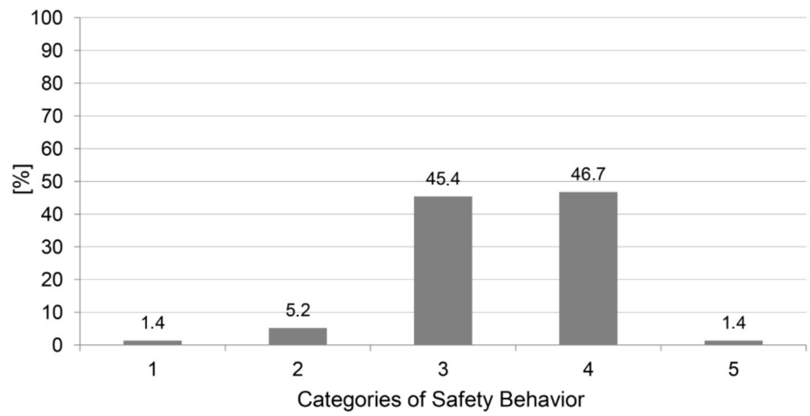

Fig. 5. Distribution of safety behavior - Safety sampling week no. 2 [Base-line Phase]

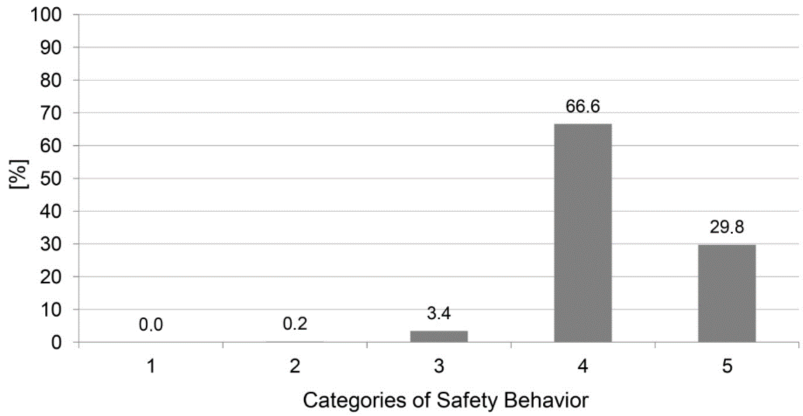

Fig. 6. Distribution of safety behavior - Safety sampling week no. 10 [Implementation Phase]

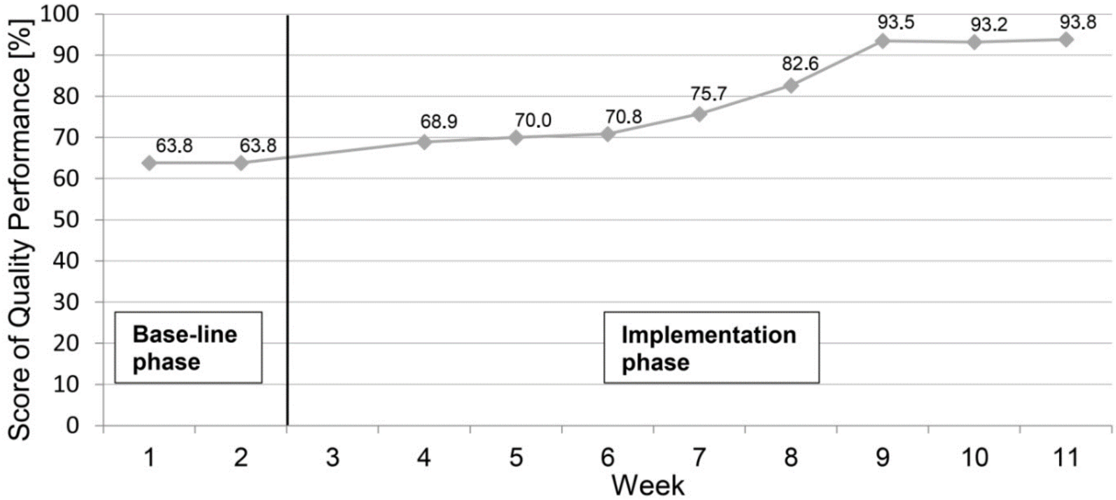

Fig. 7. Trend of weekly quality performance during phases of implementation of C^4 application

Fig. 8. Comparison of the quality of concrete works between the two phases of the study (Photographer: Igal M. Shohet)

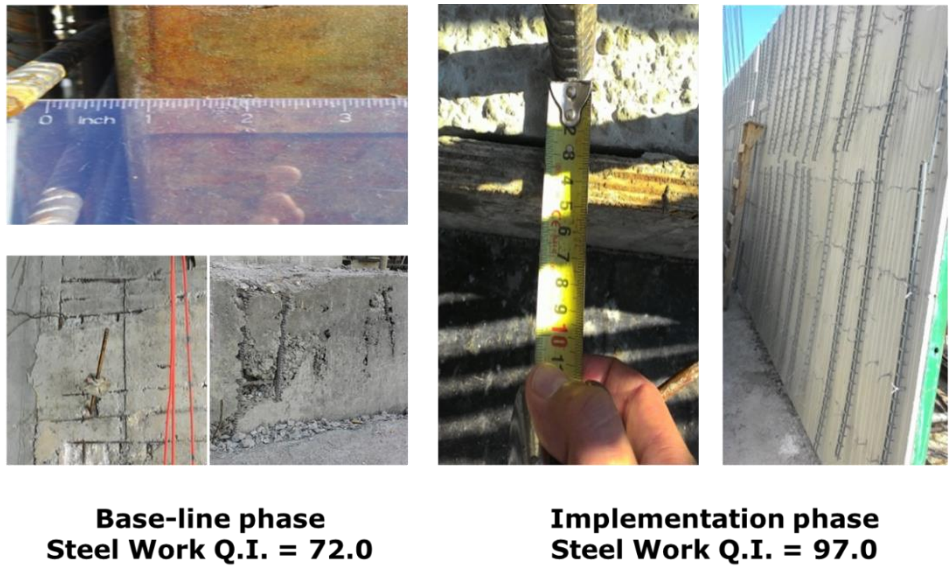

Fig. 9. Comparison of the quality of steel works between the two phases of the study (Photographer: Igal M. Shohet)