2022 European Conference on Computing in Construction
Ixia, Rhodes, Greece
July 24-26, 2022

IDENTIFYING USER REQUIREMENTS IN ORDER TO DIGITALLY ENABLE THE OFF-SITE FABRICATION OF STEEL REINFORCEMENT

Käthe-Marie White[1], and Dr Ioannis Brilakis[1]
[1]University of Cambridge, Cambridge, UK

Abstract

It is important for the success of any intervention to understand the existing system environment and user requirements. There has been limited study into the user-requirements of steel-fixers in the off-site fabrication of reinforced concrete and steel reinforcement. This work seeks to understand and specify the context in which steel-fixers are working and identify the user-requirements. Steel-fixing video footage was analysed, enabling the production of targeted questions, which were then posed to industry experts at in-person site visits. The user-requirements are categorised into three groups: the users' safety & comfort, environmental, and task-specific requirements.

Introduction

The implementation of new technologies in industry has a very high failure rate. Sailer et al. (2019) reported that many of the industry-focused studies into digital transformation found that most organisations failed in their initiatives to exploit digital technologies, with reported failure rates of 60%–85%. Similarly, approximately only 6% of proposed robotic technologies in concrete building construction research are actually implemented commercially (Gharbia et al, 2019), a number indicative of the wider problem with technology uptake in construction. Despite the low levels of uptake, there is still a lot of interest in the implementation of new technology and digital systems in the construction industry due to the promise of improvements in productivity and quality. To improve the success of any change to a process, e.g., to move it off-site, or any technological intervention, it is important to define the requirements of the process and any process users (Nguyen Ngoc et al. 2022).

This research project is about identifying the user requirements for digitally enabling off-site fabrication. User requirements, as defined by Mo et al. (2015), are the requirements of the end-user and task, the answers to the question of 'What must the system do to deliver capability?'. The authors describe 'good requirements' as being complete, they contain all the information for implementation. 'Good requirements' are solution independent, stating *what* the requirements are but not *how* they should be met; they are clear and testable, so that the requirements can be measured to determine if the design goal was met. 'Good requirements' are also traceable, meaning that it is possible to trace a requirement back to the rationale it was derived from.

'To Digitally Enable' refers to the practice of making a process possible or easier through the use of digital systems and technology. 'Off-site fabrication' specifies the process of producing or fabricating a structure, or an element thereof, at a secondary site away from the primary construction site. The secondary site is often a more controllable environment, frequently a factory specifically designed for this process (Aydinlik 2016). Off-site construction provides many benefits such as higher construction speeds, enhanced quality, and lower construction costs (Goulding et al. 2012). Razkenari et al. (2020) found that reduction in construction time was the single most important driver for off-site construction.

Shamsai (2006) reported that the rate of production for automatically manufactured reinforcement is greater than that of manually tied or welded reinforcement. It is a commonly held view that of the entire process for the fabrication of reinforced concrete, steel-fixing and cage assembly is the most challenging part to automate. Despite the benefits of automatically tied rebar, a significant portion of steel reinforcement is still manually tied or welded.

Steel-fixing is the act of positioning and securing reinforcement bars, or rebar, and other steel reinforcement (e.g. steel fabric) during the manufacturing of reinforced concrete (National Careers Service 2021). There is no 'book' on how to do steel-fixing and reinforcement cage assembly, and as such there is no single comprehensive description of the user requirements. However, certain aspects of it are covered in the documentation outlining the standards for reinforced concrete and its reinforcement. For example, BS 7973-2:2001 details the regularity and where the reinforcement should be fixed for various structures. BS EN 10080:2005, in conjunction with BS 4449:2005+A3:2016 (bar, coil and decoiled product), BS 4482:2005 (steel wire) and BS 4483:2005 (steel fabric) describes the material requirements of the steel reinforcement for reinforced concrete, while BS 8666:2020 describes the standards for the scheduling, dimensioning, cutting and bending of the steel.

State of Research

Issues with the current off-site steel-fixing process

The act of manual steel-fixing has been linked to a high risk of developing musculoskeletal issues. Solomonow et al. (2003) and Punnett et al. (1991) found that working in a static extreme trunk flexion or nonneutral trunk posture for more than 10% of working time, respectively, increases the risk of developing lower back disorders. Lower back injuries being the most prevalent musculoskeletal disorders experienced by rebar workers (Hunting et al. 1999). Studies have found that rebar workers currently spend 37 – 48% of the working time in a nonneutral trunk working posture (Burdorf et al. 1991, Buchholz et al. 2003, Forde and Buchholz 2004, Lingard et al. 2019). As such, it follows that the manual process of rebar tying leads to a high risk of musculoskeletal disorders (Umer et al. 2017).

The current automated reinforcement cage manufacturing process is not suitable for more than 2 layers of reinforcement or circular reinforcement cages (Garg and Kamat 2014). Further, Relefors et al. (2019) identified several issues with using industrial robots for the automated installation of reinforcement. In a systematic review of robotic technologies in concrete building construction Gharbia et al. (2019) found that only 22% of these technologies were commercially implemented or deemed viable by the authors. As such while there have been some attempts to address some of the problems of manual steel-fixing, including automatic rebar tying guns for muscular-skeletal issues and Building Information Modelling (BIM) for enabling understanding of project documentation, these either fail to address the full scope of issues faced by steel-fixers or have not been tested beyond prototypal stages.

Another of the current challenges in the steel-fixing process is the impact of the learning curve and the time required to understand the project build. The need to frequently refer to the approved reinforcement drawings to ensure a correct assembly is a useful and supportive task, but not one that directly results in completed work. A study on time consumption during manual steel reinforcement fabrication for high-rise buildings found that 35% of labourer time was spent on ineffective tasks, 34% on supportive or contributory tasks and only 31% on effective tasks (Nguyen et al. 2020). A significant positive relationship was also found between the quantity of reinforcement fixed (the amount bars fixed into place or tied together) and the productivity rate (Jarkas 2012). Jarkas believed that this relationship could be partially attributed to the initial 'contributory' time during which the labourers review the drawings, reinforcement details, prepare the work areas and the reinforcing steel bars before undertaking the 'direct' work. For smaller-scale activities a major portion of the labour input will go towards the initial 'contributory' work, so reducing the time spent on the 'contributory' work would allow for a significant increase in average labour productivity rates for small-scale and/or unique projects.

Potential interventions and factors impacting the user experience

One type of technology intervention with the aim of increasing worker safety is rebar-tying machines. Steel-fixers could use rebar-tying machines to reduce the risk of musculoskeletal issues. This leads to a decrease in static trunk bending and thereby decreasing the peak and cumulative compressive forces on the lower back (Vi 2003). Lingard et al. (2019) investigated the impact of tool selection on back and wrist injury risk during steel-fixing, and found that no single tool (nips, hand-held automatic rebar tying power tool, and/or long-handled stapler tool) was best in all situations and that work at different heights (in relation to the worker's body) involves different levels of risk to the back and wrist. However, Badgujar et al. (2019) reported that knots tied using automatic rebar-tying tools were less rigid and stiff than those done manually with nips.

Kwon et al. (2014) proposed an augmented reality (AR) system to manage defects within reinforced concrete (W5). This involves transferring the BIM geometry information to an AR Toolkit and then registering the AR markers to the information. Workers would next attach markers to the assigned locations in the physical world, allowing them to view the augmented BIM geometry information superimposed onto the real site components via a mobile device (W5). The authors noted that the process of setting up markers was very time consuming and suggested the use of real-time fiducial marker and markerless tracking for AR would enable faster and more convenient target detection.

Similarly, Meža et al. (2015) reported that AR can significantly contribute to the understanding of project documentation. However, technological interventions can cause discomfort to users and place them at risk if the intervention is not properly tested in the final environment. Studies have reported that the use of mobile augmented reality (MAR) in complex environments can lead to an increase in cognitive burden, such that important cues from the actual environment could be missed (Doswell and Skinner 2014, Abbas et al. 2020). This is of particular concern in a construction site where spatial and situational awareness is critical for site safety (S5). In an experiment, Abbas et al. (2020) found that rebar-drawing information provided by superimposed computer imagery helped to reduce their users' cognitive load in a 'clean' environment, compared to a paper-based (control) group. The paper-based control group took longer but were able to identify more errors than those using MAR technology due to the perception issues associated with MAR systems. Head-mounted MAR was found to decrease the users understanding of the surrounding environment and increase the inspection task completion times, not only compared to the control group but also compared to a tablet-based MAR test group. Overall, the two main existing modalities of MAR-based inspection were found to negatively affect cognitive load, task performance and situational awareness (Abbas et al. 2020). The phenomenon of simulation sickness, a subset of motion sickness, must also be considered when proposing a MAR system for head-mounted MAR devices. The choice of hardware (central processing unit, graphics processing unit and display performance) and the visual set-up (refresh rate, field of view and flicker) can impact the likelihood and severity of simulation sickness (Rangelova and Andre 2019). Incorrectly chosen hardware can increase the difficulties for users to adapt to new technology.

Kerai et al. (2020) found that when adapting to new technologies the three greatest difficulties of construction workers were: adapting to computers; a lack of motivation to accept new technology; and the way technology affects the interaction of workers in the industry. Construction managers rated the top three challenges of adapting to new technology as: poor worker attitude towards technology; resistance from staff to changes; and issues with using all the properties of new software (ibid.). The potential test groups easily available in an academic research environment (students and early career researchers) are unlikely to have the same difficulties. As an industry, construction is slow on the uptake of new technology and will rarely invest in new technology if the value is not clearly demonstratable (Heinzel et al. 2017). Frustration when technology does not do what is expected, or the user cannot figure out how to operate the system, can contribute towards barriers to uptake and communication.

Communication barriers are frequent on construction sites and pose risks to the workers' safety. Approximately 10% of the UK construction workforce are non-UK nationals (ONS 2018). This is highlighted by Health and Safety data; data from Australia, the US and the UK has found that the injury rate of migrant workers is twice that of local workers (Oswald et al. 2015). Hare et al. (2013) highlighted the issue of understanding following on from Halverson's (2003) study that training did not reduce accident rates among non-English speaking workers. If simple safety messages cannot be communicated, it can only be expected that the more complex technical messages will also get lost in translation. There are technological solutions to the communication barriers surrounding technical issues, such as neural machine translation engines or machine translation engines that use deep learning and feature extraction to provide low error and semantically correct language translations (Burlot and Yvon 2017, Du 2019). However, these solutions do not address the communication of visual cues and context that can be necessary. Miscommunication increases the likelihood of errors, increasing the number of change orders issued and impacting project success. The inclusion of technologies into construction sites and prefabrication facilities bring opportunities to increase the overall worker safety while also decreasing the unnecessary cost, time, and material wastage on projects.

Gaps In Knowledge

Through the literature review into current practice of steel-fixing and its associated difficulties, the following gaps in knowledge were identified:

- an understanding of the actual current state of practice for the off-site prefabrication of steel-fixing;
- the user requirements of off-site steel-fixing; and
- the best introduction methods for, response to and uptake rates of new technology in the UK off-site steel-fixing and prefabrication of reinforced concrete industry.

This work will address the first two gaps.

Methodology

BS EN ISO 9241-210:2019, the British Standard for human-centred for interactive systems, highlights the importance of understanding the context of use and analysing existing or similar systems as a method of revealing the constraints, needs and problems that may otherwise be missed but which still need to be addressed. To achieve this under the constraints of a global pandemic and varying levels of travel restrictions, video footage taken during 2015/16 at an off-site reinforced concrete prefabrication facility (henceforth referred to as Site 1) as part of a previous research project was used as an initial means of observation, and later supplemented with in-person site visits to two further prefabrication facilities (Sites 2 and 3). The three companies observed as part of this project include the UK's largest manufacturer and supplier of precast concrete solutions, one of the most recognised names in construction, and the fastest growing reinforcing steel fabricator in the UK and Ireland (according to their company websites and industry publications[1]). By sampling these three sites, a sufficiently detailed understanding of the industry and task of off-site steel fixing could be made for the purpose of identifying the requirements to digitally enable off-site fabrication.

I undertook a workflow analysis to both understand and specify the context of use (integrify 2021), the results of which are presented through process-mapping. The site visits were done to confirm the relevancy and usefulness of the video observations. The site visits also enabled the characteristics of the environment to be directly observed, including the way the wider environment interacts with the task. Six workers were observed assembling a total of three cages from start to finish at Site 1. A combined total of ten workers were observed at Sites 2 and 3 assembling a total of seven cages, and a further six industry experts from across the two latter sites were interviewed. The six industry experts comprised of a steel-fixing foreman, two desk-based managers at one of the sites, a steel-fixer primarily working on the cutting and bending of rebar, a steel-fixing research and development engineer for one of the sites, and a project director with extensive hands-on experience working in all the off-site steel-fixing and ancillary roles.

Multiple workers were observed showing the same behaviours, which were then corroborated through the interviews, and the combined data set (observations and interview data) was analysed with the inductive qualitative analysis methodology (Thomas 2003). Generalisability is possible on the basis of theory building (Falk and Guenther 2006) by observing and analysing data from three distinct sites, and therefore populations.

The interviews were semi-structured in nature and the questions were derived from the observations made of Site 1. The questions sought to understand motivations behind the observed practices, to answer the 'why'

1 In the participant information sheet and consent form made available to companies prior to taking part in this research, company and individual worker anonymity was assured. If required the exact citations can be made available upon request to the author, subject to company authorisation.

question posed for each observed step in a workflow analysis (integrify 2021), and to corroborate the findings from the state of practice and research literature reviews. The interviews took between 30 minutes to 2.5 hours depending on the range of steel-fixing experience and process oversight the interviewee had. The questions were originally written with a target group of interviewees who are practicing steel-fixers. Due to the difficulties in getting interviews with steel-fixers, the questions were then adapted to the available industry experts from Sites 2 and 3. This included the removal of interviewee irrelevant questions, and the simplification of language where necessary because of language barriers.

The user- and other stakeholder-needs were then identified from the context of use, the characteristics of the environment and the standards and guidelines governing the steel reinforcement and reinforced concrete industry in the UK.

Site Observations

Though the three sites differed in some of their detailed procedures, a common method was observed across all three sites (see Figure 1).

Initially upon receiving a design file, typically an IFC or PDF file (W1.1), the company/site will look at the structure to determine whether it can be built as a single large entity or will need to be broken down into sub-units. In the context of off-site fabrication, the size of structure or reinforcement unit that can be transported to the end destination site via either road or rail, often determines whether a reinforcement cage needs to be broken down.

The design file is then used to generate the schedules and workshop drawings for the workers (W1.2). Even if sites do not cut and bend their own steel (though two of the three sites observed expressed a clear preference to do so), a bar schedule is useful as it details the reinforcement bars' types and dimensions given in the workshop drawing (W1.4).

At Site 2 it was observed when cutting and bending the steel, that the shapes on the system often had to be manually adjusted to take account of the real-world behaviour of steel (W4). Figure 2 shows a comparison of a real-world bar and the adjusted computer model of the bar needed to achieve that bar. The worker operating the machine would manufacture a few bars and adjust the model manually by altering the lengths and angles until the bars are manufactured to the original schedule.

The workers were observed manually lifting and arranging temporary scaffolding supports to prepare the work area (W2.5) at Sites 1 and 2; whereas at Site 3 large, specialised scaffolding rigs would be fabricated and lifted via crane. Workers were seen to create "kit boxes", boxes or bins with all the rebar needed to fabricate a specific reinforcement cage to enable the efficient assembly of reinforcement cages. The kit box was placed in an easy access position in the vicinity of the work area as a final step prior starting the fabrication of the cage. The use of a kit box reduces the amount of time workers were spending searching for and fetching bars (W1.5).

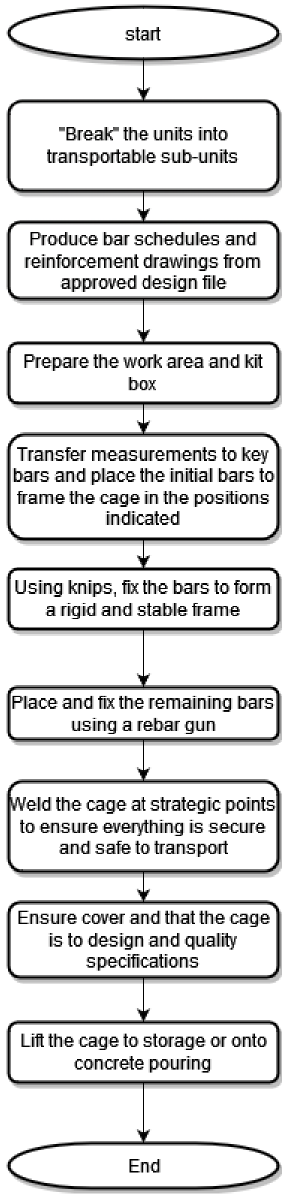

Figure 1: From the three sites combined, the process of off-site steel-fixing was observed

Workers were observed measuring the intersection points onto a reference bar and then using spray paint to transfer these measurements onto a few bars that were then placed intermittently along the length of the reinforcement cage (W1.3) in order to reduce the time spent making measurements while steel-fixing. The reinforcement cage is then "framed", which is the process of creating a stable structure with the minimum number of fixed points. Site 3 chose to use knips to fix the frame over automatic rebar tying guns as the observed strength of ties done with a rebar gun were deemed insufficient to create a stable frame. Bars frequently were observed being pulled into position due to the real-world aspects of steel, such as deviations and misalignments (W4).

The remaining bars are then placed and fixed using either rebar guns or knips. The cage is then often welded at

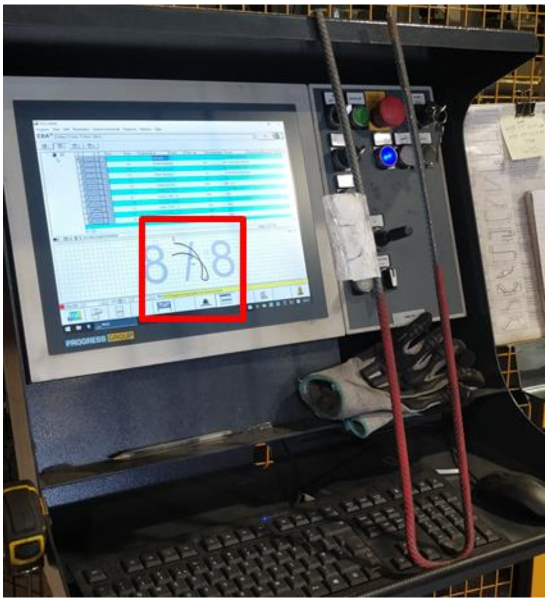

Figure 2: Comparison of real-world bar (on the right) and the adjusted computer model needed to achieve that shape at Site 2 (highlighted in red box).

strategic points to ensure it is completely rigid and can safely travel to the site without any of the bars shifting or coming loose. This is important in the realm of off-site fabrication as the fabricated reinforcement cage may need to travel significant distances to get to the end destination site. Where welding is present the site should be a member of the CARES scheme for welded reinforcement and be certified to Appendix 6 and Appendix 10 of the scheme for the in-house welding of reinforcing bars (W3.2).

After a reinforcement cage is fabricated and before it is transported to either the next stage of the off-site manufacturing process or to the end destination site, it is necessary for the cage to be checked to ensure there will be sufficient concrete cover (W3.4, the minimum distance between the exposed concrete face and the internal steel reinforcement surface or element). This may include the cutting of reinforcement bars and/or flattening of metal ties (W3.5). Additionally, the cage will be checked against the design and quality specifications to ensure that the fabricated cage is fit for purpose. All three sites had a quality checking process compliant with BS ISO 9001:2015 (BSI 2021) (W3.1). Using their existing processes and specially fabricated scaffolding, Site 3 are able to efficiently achieve accuracies of millimetre bar placement (W3.3).

The final stage of the off-site prefabrication of reinforcement cages is the transport of the cage to the next stage in the off-site production of pre-cast reinforced concrete or to the end destination site for the in-situ casting of reinforced concrete. Manual lifting of the reinforcement cages was observed at two of the three sites for smaller reinforcement cages, though mechanical lifting systems were preferred. Forklift trucks, overhead gantry systems, and cranes were all observed methods of lifting. To enable easier placement and tracking of the reinforcement cage through to its end destination, all cages would be tagged with their name and end destination (W1.7).

At each of the sites the process to clarify information from the workshop drawings was observed. This could include asking the foreman for clarification or inspecting the 3D digital model of the reinforcement cage (W1.6). It was noted that even when 3D models were available, steel-fixers preferred primarily using “traditional” 2D workshop drawings due to their inclusion of bar mark information (W1.4).

Context of Use

It was observed at two of the three sites that workers were manually lifting and adjusting the temporary scaffolding to fit each specific rebar cage. Where possible, workers used the temporary scaffolding to bring the reinforcement cage up to waist-height (S4), reducing the amount of bending required. The more complex cages with curves or non-standard angles are currently assembled at floor-level allowing the workers to draw/ mark the design on the floor to improve quality.

From discussions with the site manager, other company sites have experienced issues with the accuracy of the projection system due to vibrations and deflections to the shed structure caused by movements and usage of the overhead gantry system. For a spatial measurement or projection system to be accurate it will need to be fixed in space and isolated from vibrations and deflections of the surrounding structures (E6).

It was observed that workers were relying on paper copies of reinforcement drawings which quickly became dirty and smudged due to the working environment (E5). Construction sites and facilities are rarely clean environments by nature and Site 2 was no exception: dirt, aerosol paint sprays, oil, steel cutting sparks and welding sparks (E1) were all observed within the steel shed.

The primary language of communication in the steel shed was Russian, and except for one British national, only the steel shed foreman had more than a very rudimentary grasp of English. All communication between management and the steel-fixers was translated via the foreman. Any solution or system would need to be accessible to workers with different preferred languages and English abilities (E7).

Some commonalities were observed across the three sites. The workers and steel-fixers were always observed to be wearing the appropriate level of PPE for that point across the site: including hardhats, safety boots, high visibility clothing and ear protection where appropriate (S1, S2, S3). Even in the regions where ear-protection was not mandated, the environment was noisy (E3) and the author struggled to hear spoken conversations. Workers were observed to build multiple cages consecutively (E4), and over a reported workday from 7am – 7pm (E2), any system would need to be functional for prolonged usage and across a whole day.

Safety & Comfort (SX)		
S1		Head protection
	S1.1	PPE compatibility
	S1.2	Head-supported mass
S2		Eye and face protection
S3		Hearing protection
S4		Musculoskeletal safety
	S4.1	Reduce repetitive movements or sustained postures
	S4.2	Ergonomic equipment
S5		Awareness and comfort
	S5.1	Situational awareness
	S5.2	Vision preservation
	S5.3	Hearing Preservation

Environmental Conditions (EX)	
E1	Heat and sparks
E2	Different lighting conditions
E3	Noise
E4	Multiple consecutive builds
E5	Airborne particles, dust, dirt
E6	Vibrations to the structure
E7	Language barriers

		Task Specific (WX)
W1		Part information
	W1.1	Retrieve information from files
	W1.2	Produce rebar drawings and schedules
	W1.3	Bar location details
	W1.4	Bar information
	W1.5	Progress state and location for part or project
	W1.6	Methods to seek clarification
	W1.7	Cage information
W2		Assembly process
	W2.1	Item tracking
	W2.2	Item recognition
	W2.3	Recommend assembly sequences and fixing points
	W2.4	Generate assembly sequences and fixing points from the model
	W2.5	Preparing the work area
W3		Quality
	W3.1	Quality management system
	W3.2	CARES Appendices 6 and 10
	W3.3	Accuracy
	W3.4	Concrete cover
	W3.5	Defect and improvement identification
W4		Real-world behaviour and characteristics
W5		Model to space registration

User Requirements

Table 1 summarises the user requirements that were derived as part of this study, with the origin of the requirements is given throughout the above text for purposes of traceability. The user requirements can be broadly categorised into three groups. Those pertaining to the user's safety and comfort (SX), the environmental conditions (EX) and those that arise specifically due to the task (WX). The groupings are based upon the commonalities between the different requirements. These user requirements can be used as the basis of a designed "system" to address the previously identified issues and problems with the off-site process. The word "system" is used here to describe a possible set of processes, methods and/or technological tools that would work in tandem and encompass/ address the whole complex. Ignoring one of the "necessary" requirements will result in a non-functional system that either places the user in an unsafe situation, does not work for the end use environment or is simply not suited to the task. The derived requirements also include a number of "desirable" requirements; these are requirements that are not essential to the functioning system but will improve the overall user-experience if met.

Conclusions

This work highlights the importance of understanding all the user requirements and the context of use prior to designing a system. The high degree of replicability in general observations and patterns of behaviour across the three sites, allows for generalisation of this research to the wider off-site steel-fixing industry in the UK (Falk and Guenther 2006). Table 1 lists the user requirements that need to be met to produce a system that efficiently addresses the off-site steel-fixing complex. The absence of any necessary requirements will create a system that is not safe to use, appropriate to the environment or suited to the task at hand. Augmented reality is a potential area of research that shows potential as a solution to many of the challenges faced in the off-site steel-fixing complex; however, this research has identified the importance of considering the wider context and environment of use. This echoes the findings of Gharbia et al. (2019) and Wang et al. (2020) that more research and proposed solutions need to be taken beyond the theoretical and prototypal stages and tested in the actual end-use environments.

Limitations

This research has limitations due to multiple barriers. These barriers include the challenges involved with getting site access to off-site prefabrication environments. Due to the global Coronavirus Pandemic, not many prefabrication facilities are open to visitors. Additionally, research into construction processes frequently face barriers to *in situ* observations due to issues of site safety. The owners and contractors on construction sites in the UK have a legal obligation to ensure that everyone on-site has undergone the appropriate safety briefings and/or have constant supervision. As a result, researcher visits to construction sites and facilities places additional burdens onto the companies and individuals responsible for the sites and can result in researcher visits being declined on the grounds of time and cost.

Company secrets can often be what give one particular contractor an edge over their competitors in a very fierce industry with narrow profit margins. In order to prevent their company secrets becoming public knowledge, Site 3 restricted the data that could be collected.

Finally, there were barriers to interviewing the steel-fixers. As identified by Kerai et al. (2020), construction workers and steel-fixers are a technologically averse group. Technology that may seem second nature now to many during the last year of remote working, is still relatively alien to many steel-fixers and it was not possible for me to get any steel-fixers to agree to online interviews. Conducting interviews in-person faced the same issues as site visits, with the additional barrier that in order to interview a steel-fixer the company would effectively be a person down for the duration of the interviews. There was an additional language barrier issue that I was not explicitly informed of prior to the visit to Site 2 visit. For the above reasons, this study relied primarily on observations made of the workers supported by discussions with the 6 industry experts.

References

Abbas, A., et al. (2020). "Impact of Mobile Augmented Reality System on Cognitive Behavior and Performance during Rebar Inspection Tasks." Journal of Computing in Civil Engineering 34(6): 04020050.

Aydinlik, B. (2016). "Offsite Construction Methods and Their Benefits." https://www.ikopolymeric.com/offsite-construction-methods-and-their-benefits/ 2020.

Badgujar, V., et al. (2019). "Comparative Study on Rebar Tying Tools with Different Parameters." International Research Journal of Engineering and Technology 6(9): 318-322.

British Standards Institute (2001). "BS 7973-2:2001 Spacers and chairs for steel reinforcement and their specification - Part 2: Fixing and application of spacers and chairs and tying of reinforcement." Retrieved 04.08.21.

British Standards Institute (2005). BS 4449:2005 +A3:2016 Steel for the reinforcement of concrete. Weldable reinforcing steel. Bar, coil and decoiled product. Specification.

British Standards Institute (2005). BS 4482:2005 Steel wire for the reinforcement of concrete products. Specification.

British Standards Institute (2005). BS 4483:2005 Steel fabric for the reinforcement of concrete. Specification.

British Standards Institute (2005). BS EN 10080:2005 Steel for the reinforcement of concrete - Weldable reinforcing steel - General.

British Standards Institute (2019). BS EN ISO 9241-210:2019 Ergonomics of human-system interaction Human-centred design for interactive systems.

British Standards Institute (2020). BS 8666:2020 Scheduling, dimensioning, cutting and bending of steel reinforcement for concrete - Specification.

BSI (2021). Certificate of Registration. Quality Management System - ISO 9001:2015.

Buchholz, B., et al. (2003). "Quantification of Ergonomic Hazards for Ironworkers Performing Concrete Reinforcement Tasks During Heavy Highway Construction." AIHA journal. 64(2): 243--250.

Burdorf, A., et al. (1991). "Postural load and back pain of workers in the manufacturing of prefabricated concrete elements." Ergonomics 34(7): 909-918.

Burlot, F. and F. Yvon (2017). Evaluating the morphological competence of machine translation systems. Proceedings of the Second Conference on Machine Translation.

Doswell, J. T. and A. Skinner (2014). Augmenting Human Cognition with Adaptive Augmented Reality. Foundations of Augmented Cognition. Advancing Human Performance and Decision-Making through Adaptive Systems. S. D.D.; and F. C.M.;, Springer, Cham. 8534: 104-113.

Du, P. (2019). Elimination of Machine Translation Errors in English Language Transformation. 2019 11th International Conference on Measuring Technology and Mechatronics Automation (ICMTMA), IEEE.

Falk, I. and J. Guenther (2006). Generalising from qualitative research: case studies from VET in contexts. 15th NCVER conference.

Forde, M. S. and B. Buchholz (2004). "Task content and physical ergonomic risk factors in construction ironwork." International journal of industrial ergonomics 34(4): 319--333.

Garg, A. and V. R. Kamat (2014). "Virtual Prototyping for Robotic Fabrication of Rebar Cages in Manufactured Concrete Construction." Journal of Architectural Engineering 20(1): 06013002.

Gharbia, M., et al. (2019). Robotic Technologies in Concrete Building Construction: A Systematic Review. 36th International Symposium on Automation and Robotics in Construction (ISARC).

Goulding, J., et al. (2012). "Offsite Construction: Strategic Priorities for Shaping the Future Research Agenda." Architectoni.ca 1: 62-73.

Halverson, M. (2003). "Lost in the translation." Electr. Constr. Maint 102(6): 48.

Hare, B., et al. (2013). "Exploratory case study of pictorial aids for communicating health and safety for migrant construction workers." Journal of Construction Engineering and Management 139(7).

Heinzel, A., et al. (2017). Uses of Augmented Reality Technology during Construction Phase.

Hunting, K. L., et al. (1999). "Surveillance of Construction Worker Injuries: The Utility of Trade-Specific Analysis." Applied occupational and environmental hygiene. 14(7): 459-470.

integrify (2021). "Workflow Analysis." Retrieved 15.08.21, from https://www.integrify.com/workflow-analysis/.

Jarkas, A. M. (2012). "Analysis and Measurement of Buildability Factors Influencing Rebar Installation Labor Productivity of In Situ Reinforced Concrete Walls." Journal of Architectural Engineering 18(1): 52-60.

Kerai, U., et al. (2020). The response of the Auckland construction industry to recent technological changes. Unitec Research Symposium. Mount Albert, Auckland, New Zealand.

Kwon, O.-S., et al. (2014). "A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality." Automation in Construction 46: 74-81.

Lingard, H., et al. (2019). The impact of tool selection on back and wrist injury risk in tying steel reinforcement bars: A single case experiment, UTS ePress.

Meža, S., et al. (2015). "Measuring the potential of augmented reality in civil engineering." Advances in Engineering Software 90: 1-10.

Mo, J. P. T., et al. (2015). 3 - Systems acquisition principles. Engineering Systems Acquisition and Support. J. P. T. Mo, C. Bil and A. Sinha. Oxford, Woodhead Publishing: 37-49.

National Careers Service (2021). "Steel fixer." Retrieved 22.08.21, from https://nationalcareers.service.gov.uk/job-profiles/steel-fixer.

Nguyen Ngoc, H., et al. (2022). "Human-centred design in industry 4.0: case study review and opportunities for future research." Journal of intelligent manufacturing 33(1): 35-76.

Nguyen, P. T., et al. (2020). "Labor Productivity for Steel Reinforcement Bar of Construction Projects." Journal of Computational and Theoretical Nanoscience 17(2-3): 1163-1166.

ONS (2018). "Migrant labour force within the UK's construction industry: August 2018." from https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/internationalmigration/articles/migrantlabourforcewithintheconstructionindustry/august2018.

Oswald, D., et al. (2015). Doing the 'funky chicken' to communicate on multinational projects. 31st Annual ARCOM Conference. Lincoln, UK.

Punnett, L., et al. (1991). "Back disorders and nonneutral trunk postures of automobile assembly workers." Scandinavian journal of work, environment & health. 17(5): 337--346.

Rangelova, S. and E. Andre (2019). "A Survey on Simulation Sickness in Driving Applications with Virtual Reality Head-Mounted Displays." PRESENCE: Virtual and Augmented Reality 27(1): 15-31.

Razkenari, M., et al. (2020). "Perceptions of offsite construction in the United States: An investigation of current practices." Journal of Building Engineering 29: 101138.

Relefors, J., et al. (2019). Towards Automated Installation of Reinforcement Using Industrial Robots. 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA).

Sailer, P., et al. (2019). "Successful Digital Transformation – How Change Management Helps You to Hold Course." from https://assets.new.siemens.com/siemens/assets/api/uuid:103ce0a5-2f0b-45d7-837c-0bcc7a5083a9/version:1571666625/successfuldigitaltransformationwhitepaperbysiemensiotservices.pdf.

Shamsai, M. (2006). Prefabricated cage system for reinforcing concrete members, The Ohio State University.

Solomonow, M., et al. (2003). "Flexion–relaxation response to static lumbar flexion in males and females." Clinical biomechanics. 18(4): 273--279.

Thomas, D. R. (2003). A general inductive approach for quality data analysis.

Umer, W., et al. (2017). "Identification of Biomechanical Risk Factors for the Development of Lower-Back Disorders during Manual Rebar Tying." Journal of Construction Engineering and Management 143(1): 04016080.

Vi, P. (2003). "Reducing Risk of Musculoskeletal Disorders Through the Use of Rebar-Tying Machines." Applied Occupational and Environmental Hygiene 18(9): 649-654.

Wang, M., et al. (2020). "A Systematic Review of Digital Technology Adoption in Off-Site Construction: Current Status and Future Direction towards Industry 4.0." Buildings 10(11).