Centre for Digital Built Britain

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From Norm to Swarm: development of a balanced scorecard for evaluating automation in construction

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ERC: Dr Isolda Agusti Juan	The Bartlett School of Construction & Project Management, UCL
	i.agusti@ucl.ac.uk
PI: Professor Jacqueline Glass	The Bartlett School of Construction & Project Management, UCL
	j.glass@ucl.ac.uk
CO-I: Dr Vijay Pawar	Department of Computer Science, UCL
	v.pawar@ucl.ac.uk
CO-I: Dr Niamh Murtagh	The Bartlett School of Construction & Project Management, UCL
	n.murtagh@ucl.ac.uk

Abstract

Industry 4.0 technologies in construction (e.g. Building Information Modelling (BIM), robotics or 3D printing) offer radically different ways of planning and constructing the built environment. As a result, construction organisations expect an increase of productivity, efficiency, quality and safety, as well as a reduction of costs, emissions and waste. Yet a lack of management tools and standards to evaluate automation and set business strategic improvement drivers is hindering wider adoption in the construction industry. The aim of the project is to deliver a Balanced Scorecard (BSC) to support the adoption of automation in in the UK building industry by delivering a framework to evaluate automated construction processes from a holistic perspective (i.e. financial, social, and environmental). The BSC is co-created with industry and focuses on assessing performance indicators such as productivity, resource consumption, and GHG emissions, helping construction organisations to set improvement targets to achieve their long-term strategy. The Key Performance Indicators (KPIs) included in the BSC are tested using data from a case study of 3D printing with aerial robotics. Access to the EPSRC-funded project Aerial Additive Building Manufacturing will provide the principal dataset, supplemented by data provided by industry partners during two workshops.

Context

Recent UK governmental and industrial initiatives, such as the “Construction 2025” strategy, aim to overcome the current productivity and sustainability problems in the construction sector by developing an efficient and technologically advanced industry through the investment in smart construction and digital design (HM Government, 2013). The digitalisation of the construction industry (referred as Construction 4.0) through the adoption of construction technologies such as Building Information Modelling (BIM) is already transforming the construction industry (Eadie et al., 2013). Over the next decade, BIM will be combined with other technologies such as the internet of things and robotic manufacturing.

Although computer-controlled machines and robotic systems have started to be used in construction (García de Soto et al., 2018), the adoption of automation in the building industry has remained a marginal phenomenon (Bock, 2015). In this study, the concept of automation in construction will refer to the use of robotic systems to perform construction tasks, including technologies and applications on both ends of automatic-autonomous spectrum. Despite the potential offered by these technologies, the performance of automation in construction has not been yet investigated in a systematic manner and broader impacts remain largely unknown. The few studies that have tried to deliver a comprehensive framework to evaluate automation in construction according to the three pillars of sustainability are far from real-world applications in an industrial context (Pan et al., 2018). As a result, data uncertainty and a lack of management tools and standards in the area challenges the capacity of industrialised construction organisations to set goals, measure performance and manage changes to make their operations more sustainable. There is an urgent need for research to support the management of planning, construction and operation of building and infrastructure projects constructed with automated techniques. Understanding how these technologies can improve sustainability is essential to progress the digitalisation of the construction sector.

Automation in construction offers radically different ways of planning and constructing the built environment, but this has implications for the environment, the economy and society (García de Soto et al., 2019, Agustí-Juan and Habert, 2017). Understanding how automation can enhance productivity and efficiency in construction, while also ensuring a sustainable development, has the potential to improve performance of industrialised organisations in the round. The aim of this research project is to develop a Balanced Scorecard (BSC) (Kaplan and Norton, 2007) to be used as an evaluation framework for automation in construction and to support the establishment of quantifiable measures and targets to improve the performance of organisations, through the balanced use of automation.

Balanced Scorecard (BSC)

The need to report sustainability performance externally has led to a growing need to integrate social and environmental performance data into decision-making. Consequently, performance measurement approaches traditionally employed by organisations, such as budgeting and activity-based costing, have evolved into multi-dimensional performance measurement systems (PMS) (Bititci et al., 2012). Among PMS, Balanced Scorecards (BSCs) have been applied in major building and infrastructure projects in the UK as a means to more effectively include a broader range of criteria within project decision making. BSCs expand the evaluation criteria beyond traditional out-turn measures such as cost, time and quality to include themes related to safety, equality, environment and legacy, embedding sustainability into business strategy and supporting the main priorities of stakeholders (HM Government, 2016). The emergence of new digital and robotic technologies in construction requires a well-known and comprehensive performance management model such as the BSC to successfully handle operational and organisational changes. Such a BSC increases the likelihood that stakeholders will treat innovative construction processes more fairly and make use of them in decision-making on projects and organisational development.

Key Performance Indicators (KPIs)

Based on the literature and real demonstrators of automation in construction, a list of selected Key Performance Indicators (KPIs) was developed with the goal of integrating sustainability within an automated construction process. Table 1, Table 2 and Table 3 respectively show the selected indicators and the qualitative and quantitative data required for assessing and optimising the performance of an automated construction process in relation to each indicator. Each sustainability dimension presents the indicators in respect of three different levels:

- Operational (OP) indicators: employed to evaluate the performance of a construction process.
- Organisational (OR) indicators: relate to how the automation adoption influences the performance of an organisation.
- Societal (SO) indicators: refer to the impact of automation on society.

Table 1. Environmental KPIs for assessing automation in construction.

Indicators	Assessment data
Material consumption (OP)	material composition, material quantity (kg, m^3)
Waste production (OP)	waste composition, waste quantity (kg, m^3)
Technology production (OP)	robot type, material composition
Energy consumption (OP)	energy type, technology power (W), construction time (hours)
GHG emissions (OP)	CO_2 (kg), CH_4 (kg), N_2O (kg)
Air pollution (OP)	SO_2 (kg), NOx (kg), NMVOCs (kg), NH_3 (kg), PM_{10} (kg), $PM_{2.5}$ (kg)
Water use (OP)	water quantity (litres)
Environmental strategy (OR)	contribution to Sustainable Development Goals (SDGs)
Environmental compliance (OR)	compliance with environmental legislation
Resource scarcity (SO)	use of rare materials (high, low)

Table 2. Economic KPIs for assessing automation in construction.

Indicators	Assessment data
Material cost (OP)	material cost (£)
Labour cost (OP)	number of workers, function, salary (£)
Technology cost (OP)	hardware cost (£), software cost (£)
Operational cost (OP)	energy cost (£), water cost (£), maintenance cost (£), license cost (£)
Waste management cost (OP)	disposal/recycling cost (£)
Productivity (OP)	project dimensions (m^3) / construction time (hours), construction cost (£) / number of workers
Quality (OP)	cost of rework (£), delay (hours)
Profitability (OR)	revenue (£), market share (%)
Competitiveness (OR)	new business opportunities, dividend (£)
Innovation (OR)	R&D (£), IP (£), training (£), technology acquisition or lease (£)
Community investment (SO)	amount given as % of earnings (£)

Table 3. Social KPIs for assessing automation in construction.

Indicators	Assessment data
Health & Safety (OP)	deaths and injuries, occupational diseases, dangerous occurrences, gas incidents
Working conditions (OP)	salary and benefits, well-being, satisfaction
Workforce diversity (OP)	workers age, gender, race, disabilities (%)
Ethical supply chain (OR)	code of conduct (anti-corruption, human rights)
Social compliance (OR)	compliance with social legislation (health & safety, etc.)
Community benefits (SO)	employment increase (%)
Social acceptability (SO)	press coverage, brand reputation (positive/negative)

KPIs validation

Industry workshops

In order to explore and verify the validity and applicability of the KPIs for assessing automation in construction in the industrial context, two workshops were organised for construction industry stakeholders. For the first workshop, a group of 20 participants from major UK contractors, consulting engineers and manufacturing organisations, with expertise in sustainability, innovation, project management, automation, and business strategy working were recruited to participate in the workshop. The workshop was designed to collect individual views and to encourage active debate. The participants were divided into five working groups, each with a balanced mix of organisation types and expertise and were asked to freely organise the indicators in Tables 1-3 according to the following criteria in the context of their organisations:

- Prioritisation (from high to low): i.e. the relevance of each indicator in respect of assessing automated construction processes (see Fig. 1).
- Ease of data access (from easy to difficult): i.e. the ease with which data on a given indicator can be accessed, currently.

Furthermore, the groups had the option to add indicators to the KPIs list.

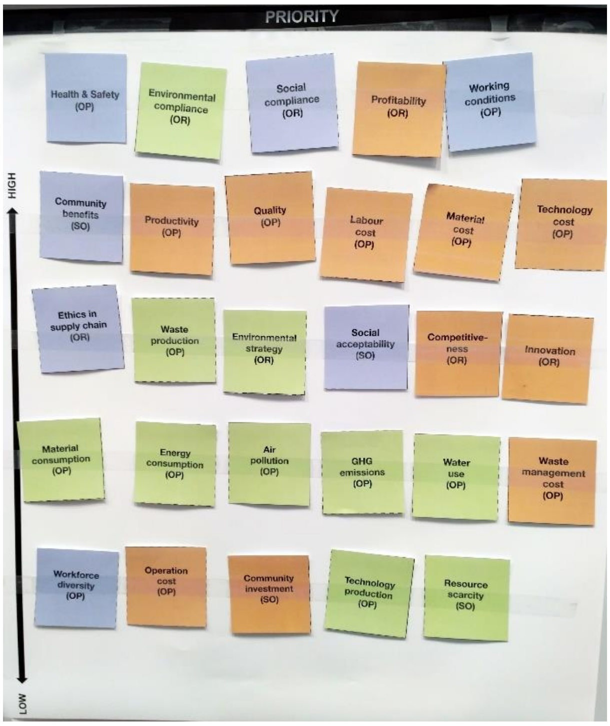

Fig. 1. Example of results from the “Prioritisation” exercise (Agustí-Juan et al., 2019).

The outcomes of the first workshop for construction industry stakeholders were used to inform an initial classification of KPIs according to priority and ease of data access (see Fig. 2).

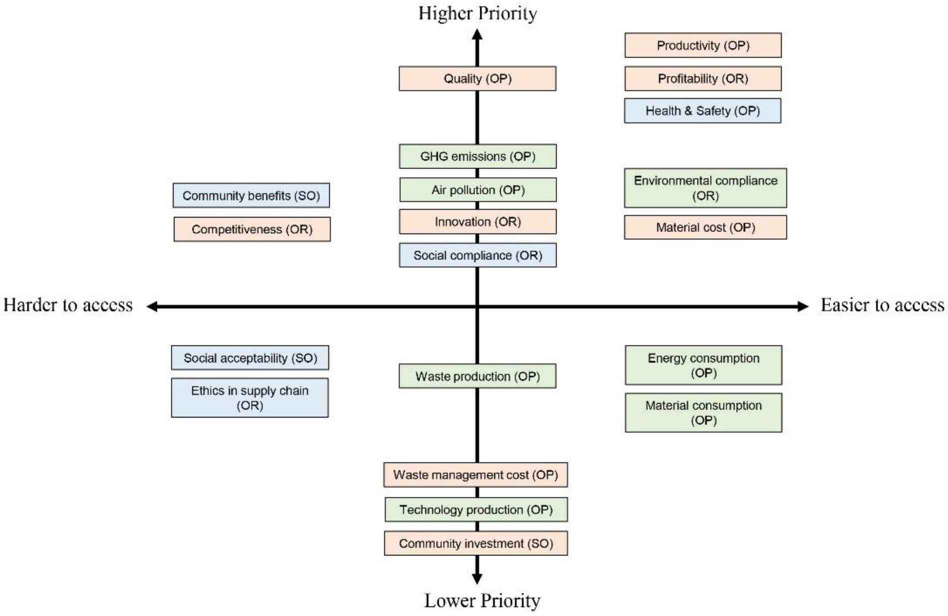

Fig. 2. Preliminary classification of KPIs for assessing automation in construction (Agustí-Juan et al., 2019).

Case study

A case study was selected to investigate the applicability of the selected KPIs for assessing automation in construction. The case study is part of the EPSRC-funded research project Aerial Additive Building Manufacturing (Aerial ABM), led by Imperial College with UCL and the University of Bath, in collaboration with BRE Trust, Buro Happold, Cementation Skanska, Dyson Ltd, and Ultimaker (EP/N018494/1). The aim of the project is to develop a multi-agent construction system that enables aerial robots to 3D print building structures autonomously (Aerial ABM, 2016). The small physical size and aerial capabilities of ABM technologies enable the manufacturing of complex building structures in diverse and difficult site scenarios (see Fig. 3). The use of swarms of aerial printers working together enables parallel production, which could reduce construction times and improve productivity. Furthermore, these technologies enable safer construction in the hard-to-access and dangerous conditions often found in building work.

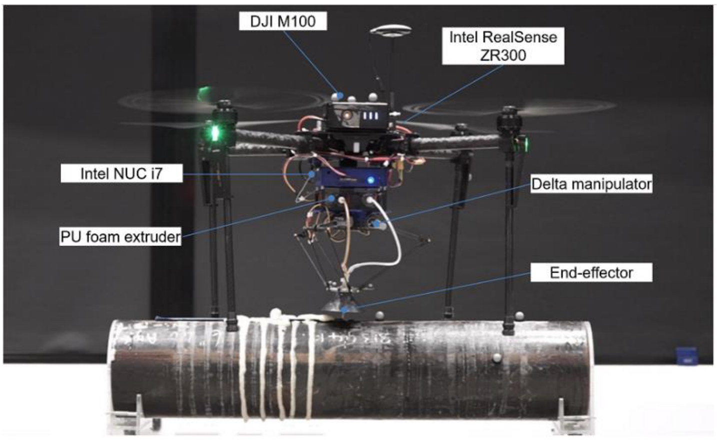

Fig. 3. Autonomous aerial robot with an integrated delta manipulator for aerial repair tasks (Chermprayong et al., 2019).

A lab prototype of Aerial ABM was quantitatively evaluated with some of the environmental and economic KPIs presented in Tables 1-2. The construction process assessed consisted of two drones that alternatively printed a lab-scale structure with cementitious mortar. Due to the experimental state of the case study, only operational (OP) indicators were evaluated. The evaluation was carried out based on data collected from the construction process, material and technology employed in the case study. This data was collected in collaboration with the Aerial ABM team at Imperial College.

Final model of BSC

In a second consultation workshop, 10 representatives of UK construction organisations were asked to evaluate the initial classification of KPIs based on priority and ease of data access (Fig. 2) and to modify it according to the criteria of their organisations. Furthermore, the case study was presented and the participants were asked to identify additional relevant indicators to be added to the evaluation (e.g. productivity) and key parameters to measure them. Based on the outcomes of this industry workshop, a Balanced Scorecard was developed, which offers an innovative method for assessing the performance of automation and robotics in the sustainability context.

The proposed final model of Balanced Scorecard (confidential due to potential publication in scientific journal) includes environmental indicators (green), economic indicators (orange) and social indicators (blue) distributed according to priority and data access. Overall, the model shows that traditional out-turn measures tend to dominate thinking among the workshop participants. The stakeholders recognise economic indicators such as Productivity (OP), Quality (OP) and Profitability (OR) as high priority measures to support decisions in organisations. The model also shows that the priority and ease of access for indicators related to compliance of regulations (e.g. Environmental compliance (OR)) is intermediate. Furthermore, the majority of environmental and social indicators tend to be deemed lower priority than all economic indicators related to costs such as Material cost (OP) or Labour cost (OP). This indicates that economic measures are still preferred to evaluate the performance of construction processes. Looking at the social and environmental measures, the data to assess social indicators (e.g. Ethical supply chain (OR)) is harder to access than environmental data, such as Waste production (OP) or Energy consumption (OP).

Looking at the indicators in more detail, Productivity (OP) is one of the indicators with highest priority for industry stakeholders. Despite this, it is classified as harder to access than other economic indicators due to the lack of a clear and standard measure to assess it. Next to traditional out-turn measures, aspects related to Health & Safety (OP) such as workforce safety and working conditions are currently highly important for construction organisations. Finally, among environmental indicators, GHG emissions (OP) are prioritised over Energy consumption (OP), although the latter is easier to access. Clearly the priority is not always influenced by data access and it may depend on how relevant is the indicator for the specific industry, in this case construction.

Relevance for a Digital Built Britain

This research should be considered as the first stage of developing a robust evaluation framework for assessing automation in construction in the industrial context. The outcome of this project provides an evaluation framework to guide academia, industry and policy makers through the transition to a digital economy, i.e. improving ways in which they leverage data and information. The BSC raises awareness and interest in automation in construction and provides a realistic vision of the impact of digital technologies and processes. Furthermore, the BSC framework will facilitate the implementation of automation in UK construction projects to improve commercial competitiveness and productivity, while ensuring the well-being of the natural environment and citizens. The application of the BSC will establish knowledge and minimum performance requirements of automated construction processes and technologies, which will serve as a base for new standards and can be transferred to UK research and education programmes.

Conclusions

The adoption of automation in construction offers potential of increasing productivity and improving value, but market adoption has been essentially experimental until now . The adoption of automation in construction requires frameworks and standards that support and guide management decisions in tune with global sustainability development trends.

The proposed Balanced Scorecard (BSC) model uses a hierarchic set of KPIs from the three dimensions of sustainability at three assessment levels, which provide a holistic understanding of the impact of automated construction processes and facilitates a new pathway for achieving sustainability in buildings. The prioritisation of indicators supports management teams in decision-making regarding the adoption of automation and in defining relevant issues to be targeted and optimised in the organisation. The development of the BSC based on industry stakeholders’ views ensures the applicability of the framework for assessing the performance of automation in the industrial context. Furthermore, the evaluation of a case study confirms the effectiveness of the BSC model by highlighting the relevant data to be measured and transferred throughout the value chain (design-construct-operate-maintain) of the organisation. The final goal of the BSC is to facilitate the implementation of automated and robotic construction processes to improve productivity, while ensuring the well-being of the environment and society.

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