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A Simple Framework for the Cost–Benefit Analysis of Single-Task Construction Robots Based on a Case Study of a Cable-Driven Facade Installation Robot

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Abstract: Single-task construction robots (STCRs) have become a popular research topic for decades. However, there is still a gap in the ubiquitous application of STCRs for onsite construction due to various reasons, such as cost concerns. Therefore, cost–benefit analysis (CBA) can be used to measure the net economic benefit of the STCRs, compared to traditional construction methods, in order to boost the implementation of STCRs. This paper presents a simple and practical framework for the economic evaluation of STCRs and conducts a case study of a cable-driven facade installation robot to verify the method. The results show that the cable-driven robot for facade installation is worth investing in in the UK, as well as in the majority of G20 countries. Furthermore, other socioenvironmental implications of STCRs and the limitations of the study are also discussed. In conclusion, the proposed method is highly adaptable and reproducible. Therefore, researchers, engineers, investors, and policy makers can easily follow and customize this method to assess the economic advantages of any STCR systems, compared to traditional construction technologies.

Keywords: cable-driven parallel robot; construction robot; cost–benefit analysis; curtain wall modules; economic evaluation; facade installation

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1. Introduction

Ever since the first debut in the 1970s in Japan, single-task construction robots (STCRs) have become a worldwide research and development topic. They are robots or automated devices that are developed primarily for tasks on the construction sites [1]. It is a highly cross-disciplinary field which requires an integration of a variety of knowledge and expertise such as civil engineering, architecture, industrial design, construction management, robotics, mechanical engineering, electrical engineering, and informatics. Today, the application fields of STCRs continue to expand. For instance, Bock and Linner summarized 200 existing STCR systems into 24 categories based on their functions [2]. However, currently, there is still a gap in the ubiquitous application of STCRs for onsite construction due to various reasons, such as insufficient proof of net economic benefits, lack of modularity in building components, lack of skilled labor for operation, incompatibility with other construction tasks, and time-consuming onsite setup [2]. Therefore, more research evidence is needed to prove the net economic benefit of the STCRs, compared to traditional construction methods, in order to boost the speed and breadth of the implementation of STCRs. Cost–benefit analysis (CBA) is oftentimes considered as one of the most important problem-solving tools in decision-making processes, yet there is a lack of research on the quantitative evaluation of STCR systems to study their economic implications for key stakeholders. This paper aims to propose a simple methodological framework for the cost–benefit analysis of STCRs based on the case study of the onsite cable-driven facade installation robot developed in the EU research project named Hephaestus.

Cost–benefit analysis (CBA) is commonly used for economic evaluation of a project or policy. It can be dated back to the mid-19th century by French engineer and economist Jules Dupuit [3]. It is a policy assessment tool that monetizes all impacts of a project or policy to all relevant stakeholders in society [4]. According to Munger, CBA is considered as the "single most important problem-solving tool in policy work" [5]. The CBA usually can be divided into several major steps in order to make the process more manageable. The steps can usually be described as follows [4].

- Specify the set of alternatives projects.
- Decide who will be the key stakeholder for the benefits and costs.
- List impacts and determine ways to measure them.
- Predict impacts quantitatively over the life of the project.
- Monetize every impact.
- Discount benefits and costs to obtain present values.
- Calculate the net present value of each alternative.
- Perform sensitivity analysis.
- Make a recommendation.

Like every assessment tool, CBA has certain limitations, such as its imperfect process, its monetization of non-market articles, the openness of the results, the thorough examination by the public, its dependence on correctness and completeness, the difficulty of being understood, its ethics, and its neglect of long-term environmental impacts [4]. Nevertheless, considering its wide usage in the policy-making activities, it is naturally reasonable to apply CBA as a tool to evaluate the economic benefits of STCR systems.

2. Literature Review

With regard to the construction industry, there have been several instances of CBA research available to the public. In particular, Shen et al. compared the costs and benefits of prefabricated public housing projects and traditional housing projects based on survey and field research [6]. The research reported an analysis of construction costs and environmental benefits of prefabricated housing, largely based on collected questionnaires from more than 50 managers, which takes a great amount of efforts. Li and Mandanu proposed an uncertainty-based methodology for the life-cycle CBA of highway projects that handles certainty, risk, and uncertainty [7], which requires accessing a large amount of historical data. In addition, Medici and Lorenzini proposed a mathematical model for optimizing energy-saving measures on the building envelope, which reveals the relationship between energy benefit and the related cost [8]. With regard to construction automation, Jang and Skibniewski conducted a CBA of an embedded sensing system for construction material tracking, compared to manual materials tracking, method based on interviewing the experts regarding labor productivity [9]. Another interesting research by García de Soto et al. compared the productivity of robot fabrication to that of manual technique in building complex concrete walls [10], but, strictly speaking, it is a cost and time analysis rather than a comprehensive CBA. Furthermore, Kim et al. developed an assessment tool to evaluate the economic efficiency of an integrated automated onsite construction system [11], focusing on assessing an integrated automated construction system rather than a specific STCR.

These precedents provide insightful knowledge of economic evaluation for the construction sector. However, few of these methods are specifically designed for conducting the CBA of STCR systems, due to the lack of accumulated information in practical applications of construction robots, even though the research field of STCR systems is becoming more popular in recent years.

Therefore, developing a practical method of CBA for evaluating STCR systems would be beneficial to both academia and industry. The goal of this research is to explore a simple framework for the cost–benefit analysis of STCRs, compared to conventional methods, which can be quickly adapted and used for evaluating other STCR systems. The framework will be verified in the case study of onsite facade installation performed by the cable-driven robot developed in the Hephaestus project. The results of the case study can help determine whether the Hephaestus robot is worth investing in for construction companies. More importantly, this framework can be easily adapted to evaluate other STCR systems in various contexts. Furthermore, the results can provide evidence for the policy makers to decide how many resources shall be allocated or invested to the research and development of automated construction technologies.

3. Methods

As mentioned above, this research aims at proposing a simplified method for performing the economic evaluation for construction robots. In this section, the analytical framework and cashflow analysis table for calculation are proposed in general, which, later, is applied to the case study thereafter.

3.1. Analytical Framework for the CBA

In order to compare the STCR solutions to the conventional construction methods, the following simple and practical analytical framework for CBA is proposed (see Figure 1). The CBA in this article will follow this analytical framework.

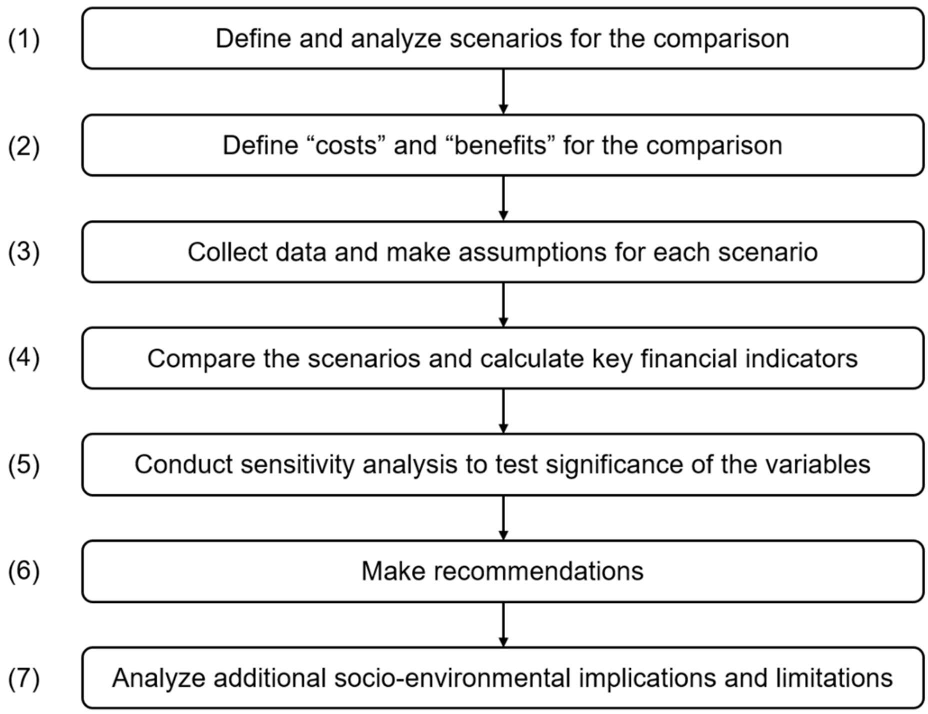


Figure 1. The analytical framework of cost–benefit analysis (CBA) applied in this research.

3.2. Cashflow Analysis Table

In the calculation process of the CBA, all relevant factors that affect the main stakeholder need to be considered. Normally, the cashflow analyses for CBA range from at least three (small-scale projects) to more than ten years (e.g., large-scale public projects) [7,12,13]. The five-year calculation period here is mainly because the engineering partners in the project estimate that the lifecycle of such types of construction robots will likely be approximately five years. More importantly, for individual companies as the key beneficiaries, the investment will not be attractive for them if the payback period is longer than five years (e.g., 10 years or above). Therefore, five years is a reasonable time horizon for economic evaluations of STCRs. As a result, a comparison table between conventional methods and STCR solutions is designed which takes every factor during the onsite construction task into consideration in a five-year period (see Figure 2).

Cashflow analysis to compare novel STCR solution and conventional method							
Key stakeholder/beneficiary							Operating region
Cash outflows	Year 1	Year 2	Year 3	Year 4	Year 5	Total (€)	Explanation and remarks
Central - hardware costs							
Central - software costs							
Central - network costs							
Central - utility costs							
Central - operation							
Central - maintenance							
Central - other							
Per robot costs - hardware							
Per robot costs - software							
Per robot costs - network & utility							
Per robot costs - training							
Per robot costs - transport							
Per robot costs - installation							
Per robot costs - operation							
Per robot costs - disassembly							
Per robot - maintenance							
Per robot - other							
Total outflow							
Savings - equipment							
Savings - labor							
Savings - utility							
Savings - operational							
Savings - maintenance							
Savings - other							
Total savings							
Net annual cashflow							
Net cumulative cashflow							
Coefficient of productivity							
Annual wage increase							

Figure 2. Template of the cashflow analysis.

In this template, the light grey cells indicate the cost and saving aspects that need to be taken into consideration, whereas the white cells are used to input values for each cost and saving aspect in the respective year. Each line of item is followed by an "explanation and remarks" cell to describe the respective item in detail (e.g., explanation, calculation, additional information, etc.)

In particular, in the cash outflow category, the "central" rows indicate the indirect costs that a construction company needs to bear in their headquarters in order to run each robot system for a specific task each year, whereas "per robot costs" rows indicate the direct costs of each robot system each year. The "savings" rows indicate the costs of conventional construction method to conduct the same task each year. The "explanations and remarks" row can be used to explain how each row is calculated. If by, or before, year 5 the net cumulative cashflow turns from negative to positive, it suggests that the STCR system is likely to be worth investing in. Furthermore, based on the result of this table, key financial indicators can be calculated accordingly.

In the next section, a case study of an STCR project for facade installation is conducted, and a CBA of the STCR system is performed, based on the proposed framework, in order to verify the method.

4. Case Study

After the comparison framework is defined, a case study comparing the conventional curtain wall installation method and the alternative Hephaestus cable-robot solution is conducted, as follows.

4.1. Curtain Wall Installation Process

A curtain wall is an exterior envelope of the building that does not carry any vertical loads of the roof or floor. It supports its own weight as well as other imposed loads, such as wind, and transfers these forces to the building structure. It provides benefits such as daylight shading, insulation, and weight reduction [14]. Normally there are two types of curtain wall installations: (1) the stick system, where the assembly of the curtain wall components such as frames and glass panes, takes place on site; (2) the unitized modular system, where the prefabricated curtain wall modules (CWMs) are installed onsite. Due to the scope of this research, only the unitized prefabricated module system is considered. The standard CWM installation consists of four main steps, which are (1) bracket installation, (2) lifting the CWM, (3) CWM installation with position adjustment, and (4) CWM unit fixation (see Figure 3) [15].

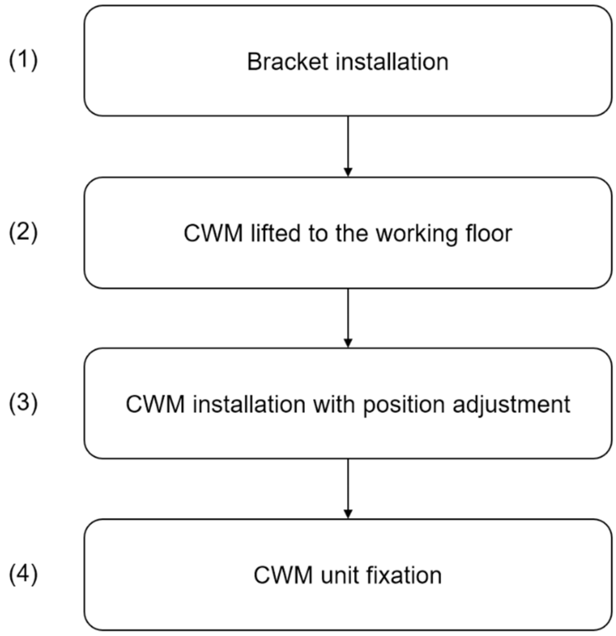


Figure 3. Four main steps in the curtain wall module (CWM) installation.

4.2. Conventional CWM Installation

In the first step of installation, the brackets will be manually installed to the building floors. There are two main techniques for bracket installation: the cast-in channel technique and the drilling technique. In the cast-in channel technique, the channels are welded onto the rebars of the framework before pouring the concrete, whereas the drilling technique requires drilling holes based on pre-measured drilling points which avoid rebars underneath. In the context of this research, only the drilling technique is involved. During the bracket installation process, the position of the CWM will be checked and controlled by using measurement systems such as a total station. The placement of the brackets is critical and will likely not be readjusted later. In the meantime, the modules will be transported to the construction site and stored after being unpacked and assembled. In the second step, the CWM will be lifted by the crane to the working floor (or, alternatively, in some cases, be elevated to the working floor through an elevator if possible). In the third step, while the crane holds the weight of the CWM, workers on the working floor minutely adjust the position of the CWM to ensure its installation to the brackets. Finally, after the position of the CWM is correctly confirmed, workers on the working floor fix the unit and the next CWM installation starts (see Figure 4) [15].

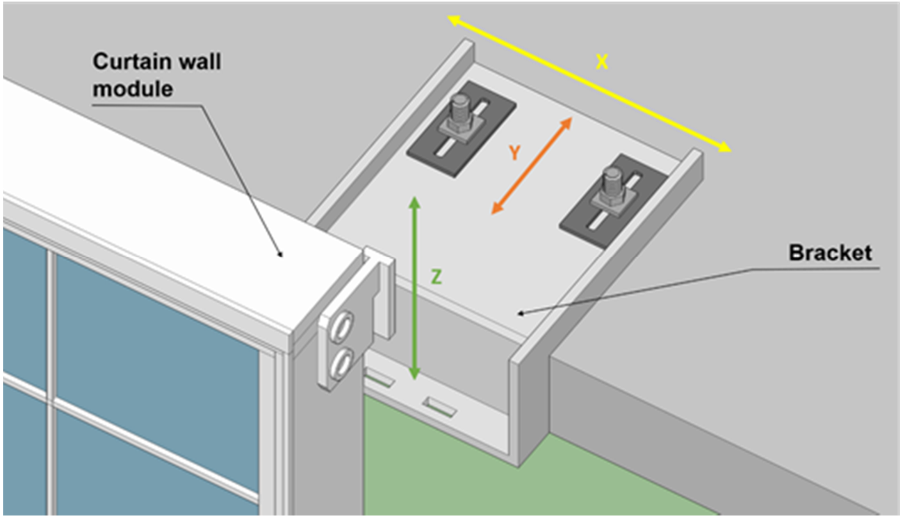


Figure 4. Schematic diagram of a typical bracket on the concrete building floor and its connection with a CWM module (the drilling technique).

Therefore, in the conventional CWM installation process, all the four steps are done manually by workers with the help of certain machines. The installation of brackets is completed by workers one by one manually, which is highly time-consuming. As demonstrated in Figure 5, the manual method normally involves several workers to work together at height, creating high labor costs and potential danger for these workers (e.g., injuries caused by machinery, back injuries from heavy lifting, falls from height, hearing loss from long-term exposure to loud machinery, etc.). In addition, workers on the ground, for component handling, and a tower crane, for CWM positioning, are necessary as well.

Figure 5. Several workers working at height during the CWM installation process (facade installation in Solar Carve Tower, New York. Facade engineered and manufactured by Focchi Group; photo by Timothy Schenck).

4.3. Automated CWM Installation

There are several existing instances of automated curtain wall installation. For example, a patented method developed by Brunkeberg Systems AB uses a dedicated railing system to automatically install specially-designed CWMs from the outside of a building [16]. However, the railing installation process is manual, and might not apply to certain types of buildings. Other researchers reported a mobile robot that can perform facade installation from the inside of the building, but it only managed to automate the third step, which is positioning the CWM. Činkelj et al. developed a hydraulic telescopic system that installs facade panels to the building from the outside. However, this semi-automated, tele-operated system is specialized for handling facade panels rather than CWMs, and there is also a height limitation due to the use of a telescopic handler [17]. In addition, researchers also proposed other novel solutions for the automatic installation of the facade, but many are still at conceptual level [18–21].

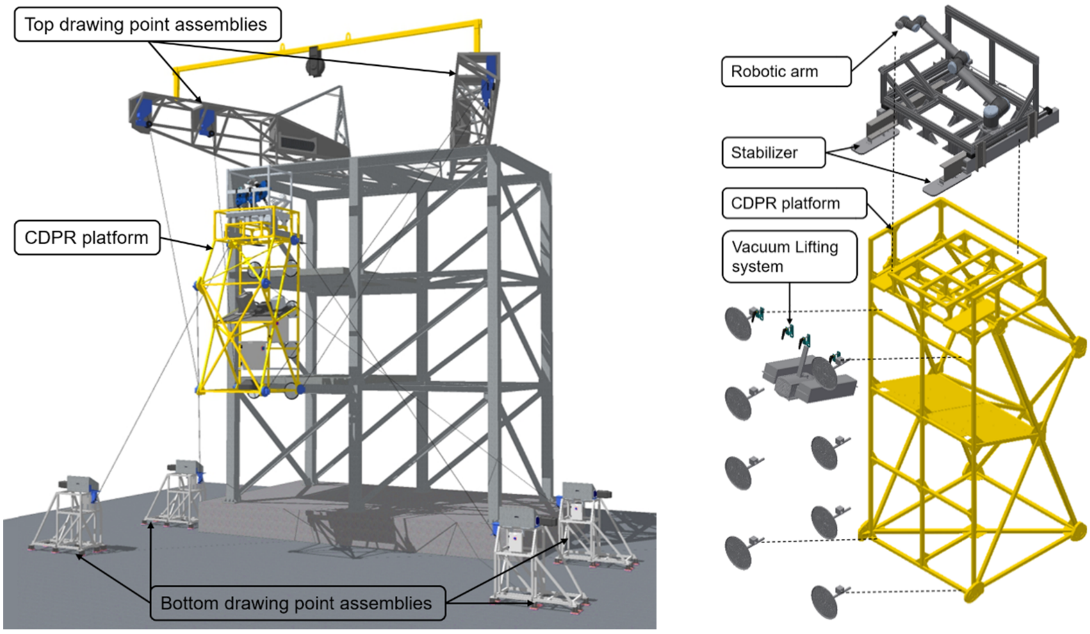
Therefore, the Hephaestus cable-driven robot was primarily developed for the CWM installation task, although various functions can be achieved by reprogramming the robot and replacing the end-effector. It is arguably the first cable-driven parallel robot (CDPR) in the world that is designed, built, and deployed specifically for curtain wall installation.

The CWM installation, as explained above, consists of four main steps: bracket installation, panel lifting, position adjusting, and panel fixation, which are the main tasks of the Hephaestus robot. The advantages of the robot are the large range of workspace, high payloads, reconfigurability, and modularity, making the system easily transportable and highly adjustable to adapt to various situations.

In terms of geometry, a CDPR is a configuration of cables with variable lengths connecting a drawing point attached to the base frame, and a fixing point attached to the mobile platform. The geometrical design of the CDPR can be defined by the following parameters: (1) number of cables, (2) geometry of the structure, (3) geometry of the platform, and (4) cable configurations. Previous studies indicate that CDPR driven by eight cables will have appropriate performance, thus the number of cables was chosen [22]. The geometries of the structure and platform were determined by the positions of the drawing points and attachment points, respectively.

The Hephaestus CDPR consists of seven subassemblies. There are two drawing point assemblies on the top of the building, and four on the bottom, controlling the lengths of the cables (see Figure 6a). In the center is the working platform subassembly, featuring eight fixing points, as well as the power system and various tools for the modular end-effector. In the Hephaestus project, two major tasks need to be performed: (1) the fixation of the bracket onto the concrete slab, which is performed by the robotic arm (see Figure 7), and (2) the placement of the CWMs onto the brackets by a vacuum system attached to the bottom of the CDPR platform (see Figure 6b). In addition, a linear system with vacuum cups serving as a stabilizer is also integrated in the platform in order to stabilize the working platform subassembly (see Figure 8) [23].

In addition, the CDPR features a control room (i.e., a small movable container equipped with computers and other relevant devices) which serves as the "brain" of the system. Currently, the CDPR (prototype) does not directly integrate advanced digital construction technologies. The main tasks, such as bracket installation and CWM positioning, are preprogrammed based on traditional CAD drawings. However, since the CDPR is equipped with adequate hardware and software capabilities, it certainly has the potential to integrate digital construction technologies, such as building information modeling (BIM) and digital twin, in future iterations in order to enhance its speed and performance.



(**a**) (**b**)

Figure 6. (**a**) Design of the Hephaestus cable-driven parallel robot (CDPR) prototype; (**b**) detailed depiction of the modular end-effector of the CDPR system.

Figure 7. Robotic arm and its tools for bracket installation protected by weatherproof covers (photo: José David Jiménez-Vicaría).

Figure 8. Stabilizer attaching the robot platform to the concrete slab (photo: José David Jiménez-Vicaría).

4.4. Determining the Scenario for Evaluation

Based on discussions and communications with partners of the Hephaestus project, a presumptive scenario for comparison can be proposed, as below (see Table 1). In this scenario, it is assumed that the facade installation company (i.e., Focchi Group UK) owns the robot during its lifecycle, because the company generated 133.90 million US dollars in revenue in 2019, which is large enough to fully employ more than one Hephaestus robot system.

In the case of curtain wall installation, the service charge is highly case-dependent (i.e., not only decided by the working area, but also by the form and shape of facade, type of CWM, etc.) and thus not easy to determine broadly. Usually, the representatives at the construction company carefully evaluate the building and requirements and provide an offer to the client thereafter. Therefore, a situation is assumed where the two scenarios execute exactly the same amount of workload (thus yielding the same revenue) based on the productivity of one robot system. In this way, many uncertainties can be avoided in determining the revenue that the company can make in the two scenarios. Similar to the concept of a controlled experiment in biology, in this research the variable "revenue" is controlled. Then, the costs of adopting the robot system and the benefits of saving money by avoiding the conventional method are compared. In other words, the costs here equal the money spent to operate the robot system, and the benefits equal the money saved by not using the conventional CWM installation method.

Table 1. Conventional and alternative scenarios defined for the comparison.

Category	**Scenario 1**	**Scenario 2**
Name	Hephaestus cable-driven robot	Conventional facade installation
Key beneficiary	Facade installation company (Focchi Group UK)	
Business model	Owning the robot	Paid based on working area, etc.
Primary location for calculation	United Kingdom	
Investment period	5 years (the assumed lifecycle of the robot according to the engineering partners in the project)	
Main equipment required	1 cable-driven robot	1 crane for positioning
Estimated average area per job	540 m^2 (L30 m × H18 m; 1.5 m × 3 m per panel)	

4.5. Gathering Data and Proposing Assumptions for Calculating the Costs of the Conventional and Alternative Scenarios

The data needed for the calculation in the cashflow analysis table are collected by various means such as market research, online meetings, calls, and emails with key stakeholders (e.g., the facade installation partner, the robot developing partner). Based on the data-gathering activities, the following information, which is crucial to the calculation, is demonstrated in Table 2.

Table 2. Data collected for the cashflow analysis of the two scenarios.

Category	Scenario 1	Scenario 2
Name	Hephaestus cable-driven robot	Conventional facade installation
Number of workers	• 3 workers for system setup and disassembly; 1 worker for robot operation	• 1 for crane operation; 5 for curtain wall module handling
Speed/performance	• ~15 min for one bracket installation • ~15 min for one CWM installation	• ~30 min/m^2
Total time needed per job	• 123 h in total: • 55 h setup • 60 h curtain wall installation • 8 h disassembly	• 270 h
Productivity weight coefficient	1	2.20
Jobs finished per year	14	6.36
Downtime per year (e.g., holidays, operational, extreme weather, etc.)	8 weeks	
Median wage of construction worker in the UK	15.47 € (14.05 GBP) per hour	
Annual wage increase	3% (commonly applied in the construction sector)	
Discount rate	0.1% (in the UK as of October 2020)	
Annual equipment maintenance costs	10%	

Note: In addition, detailed explanations of Table 2 are listed as follows.

1. The main financial beneficiary is a curtain wall installation company operating in the UK, because the main market of facade installation for the key beneficiary is in the UK.
2. For the simplification of calculation, the table uses the median hourly rate of construction workers to calculate all the inputs related to labor costs.
3. The estimated cost of the robot system includes manufacturing cost, logistics, administrative cost, and profit.
4. The robot system does not cause extra administrative costs, compared to the conventional method.
5. A one-month training cost of 12,000 € (3000 €/person) is added, to train four workers for operating the robot system during the downtime of the first year. During the training month, these workers' salary needs to be covered by the company as well (9900 €). After the training, one worker will become a highly-skilled operator, thus earning 30% more salary than the average worker.
6. The annual total saving outputs equal the annual saving inputs multiplied by a productivity weight coefficient of 2.2, which means that the alternative robot system is 2.2 times as productive as the conventional method. Therefore, the productivity weight coefficient needs to be considered in the conventional method to keep up with the productivity of the alternative robot system in order to achieve the same gross revenue for fair comparison.

7. Regarding the central cost for the company, this robot system does not require additional special managerial efforts, compared to the conventional scenario. Therefore, central costs are not calculated in both scenarios.

5. Results

Based on the proposed comparison scenario and collected data in the case study, the following results can be presented, including cashflow analysis, key financial indicators, sensitivity analysis, and recommendations. According to the comparison of the conventional method and cable-driven robot method for facade installation, the cashflow analysis table can be filled in detail with corresponding numbers, as below (see Figure 9).

Cashflow analysis to compare novel STCR solution and conventional method							
Key stakeholder/beneficiary	Curtain wall installing company						Operating region: UK
Cash outflows	Year 1	Year 2	Year 3	Year 4	Year 5	Total (€)	Explanation and remarks
Central - hardware costs						0.00	
Central - software costs						0.00	
Central - network costs						0.00	
Central - utility costs						0.00	
Central - operation						0.00	
Central - maintenance						0.00	
Central - other						0.00	
Per robot costs - hardware	600,000.00					600,000.00	
Per robot costs - software						0.00	
Per robot costs - network & utility	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	15,000.00	
Per robot costs - training	21,900.00					21,900.00	
Per robot costs - transport	5,000.00	5,000.00	5,000.00	5,000.00	5,000.00	25,000.00	
Per robot costs - installation	35,735.70	36,807.77	37,912.00	39,049.36	40,220.85	189,725.68	
Per robot costs - operation	16,893.24	17,400.04	17,922.04	18,459.70	19,013.49	89,688.51	
Per robot costs - disassembly	5,197.92	5,353.86	5,514.47	5,679.91	5,850.30	27,596.46	
Per robot - maintenance	60,000.00	60,000.00	60,000.00	60,000.00	60,000.00	300,000.00	
Per robot - other						0.00	
Total outflow	747,726.86	127,561.67	129,348.52	131,188.97	133,084.64	1,268,910.65	
Savings - equipment	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	250,000.00	
Savings - labor	159,390.50	164,172.22	169,097.39	174,170.31	179,395.42	846,225.83	
Savings - utility	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	5,000.00	
Savings - operational						0.00	
Savings - maintenance	5,000.00	5,000.00	5,000.00	5,000.00	5,000.00	25,000.00	
Savings - other						0.00	
Total savings	473,859.11	484,378.88	495,214.25	506,374.68	517,869.92	2,477,696.83	
Net annual cashflow	-273,867.75	356,817.22	365,865.73	375,185.70	384,785.28	1,208,786.18	
Net cumulative cashflow	-273,867.75	82,949.47	448,815.20	824,000.90	1,208,786.18	1,208,786.18	
Coefficient of productivity	2.20						
Annual wage increase	1.03						

Figure 9. Cashflow analysis of the proposed robot system based on the UK market.

5.1. *Key Financial Indicators of the Hephaestus Cable Robot*

As mentioned above, the key financial indicators relevant in this evaluation can be calculated based on the results of the cashflow analysis (Figure 9), including benefit–cost ratio (BCR), return on investment (ROI), payback period (PBP), initial investment value (IIV), and net present value (NPV) [4]. The key financial indicators are calculated based on the following equations:

$$\text{BCR} = (|\text{present value of benefits}|)/(|\text{present value of costs}|) \quad (1)$$

$$\text{ROI} = (\text{total cost savings} - \text{total outflows})/(|\text{total outflows}|) \quad (2)$$

$$\text{PBP} = \text{n} + (|\text{net accumulative cashflow of year n}|)/(\text{net annual cashflow of year n} + 1), \\ \text{n represents the number of the final year with negative net accumulative cashflow.} \quad (3)$$

$$\text{IIV} = (\text{initial hardware cost}) + (\text{initial deployment cost}) \quad (4)$$

$$\text{NPV} = (\text{net annual cashflow})/(1 + \text{cost of money})^{\text{Years in the future}} \quad (5)$$

As a result, the key financial indicators of the Hephaestus cable-driven robot for curtain wall installation are calculated, as below (see Table 3).

Table 3. Key financial indicators of the proposed robot system when operating in the UK.

Key Financial Indicator	Value
Benefit–Cost Ratio (BCR)	1.95
Return on Investment (ROI)	95.26%
Payback Period (PBP)	21.21 months
Initial Investment Value (IIV)	747,726.86 €
Net Present Value (NPV)	1,205,040.19 €

Note: The definitions of the key financial indicators are listed as follows:

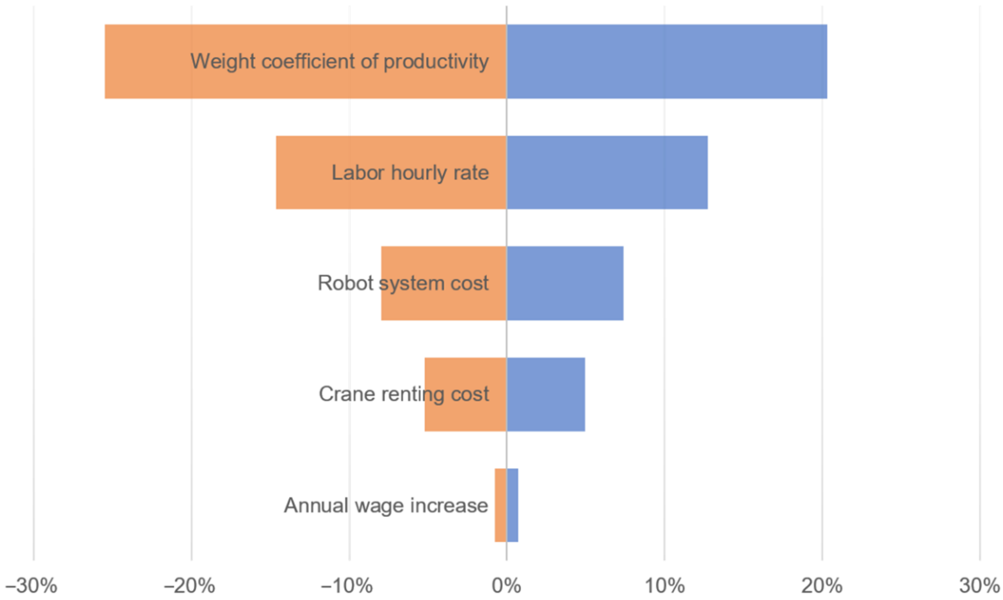
1. BCR indicates the overall relationship between the relative benefits and costs of a proposed project. In this case study, benefits refer to the money saved by not using the conventional facade installation method, and costs refer to the money spent to operate the robot system. If the value is larger than 1.0, the project is expected to deliver economic satisfaction to its investors.
2. ROI is a performance measure used to evaluate the efficiency of an investment.
3. PBP is the period of time required to recover the cost of an investment.
4. IIV is defined here as the amount of money needed for the total capital expenditures in the first year.
5. NPV is the current value of a future stream payments. Here it refers to the present value of the total net accumulative cash flow.

5.2. Sensitivity Analysis

Sensitivity analysis, also known as what-if analysis, is a financial tool which determines how target outputs are affected based on changes in input variables. This model is used to predict the result of a decision, given a certain set of variables. There are a wide range of uses of sensitivity analysis, which can be categorized into four main aspects: decision-making support, communication, increasing understanding of the system, and model development [24]. Based on this tool, the analyst will be able to understand which input variable is more consequential, and which one is less.

Therefore, a simple sensitivity analysis is conducted, regarding several major variables in the cashflow analysis. By adjusting each input variable 10% better and 10% worse, the total accumulative cashflow by the end of the five-year period will also change accordingly. Thus, the increase and decrease of total accumulative cashflow, compared to the original estimation, can be calculated. In this case, five main input variables, including annual wage increase, labor cost (hourly rate), robot system cost, crane renting cost, and productivity coefficient weight, are evaluated. The result is shown in Figure 10.

From the sensitivity analysis, it can be concluded that the outcome is most sensitive to the weight coefficient of productivity, followed by labor hourly rate, robot system cost, crane renting cost, and last, but not least, the annual wage increase. Other variables, such as utility cost and training cost, are not listed here due to their relative insignificance to the outcome of the analysis. The sensitivity analysis is especially important and insightful because many data acquired in this study are only rough estimations. It indicates that the most efficient way to improve profitability or benefits of the alternative system is to further improve the productivity and efficiency of the robot, although this objective might be difficult to achieve.



	Annual wage increase	Crane renting cost	Robot system cost	Labor hourly rate	Weight coefficient of productivity
Positive	1%	5%	7%	13%	20%
Negative	−1%	−5%	−8%	−15%	−26%

Figure 10. Sensitivity analysis of the CBA.

5.3. Recommendations

As mentioned in the beginning of this paper, the last part of CBA, usually, is to make a recommendation on whether the alternative option is worth considering. The results of key financial indicators indicate that the BCR is 1.95, which exceeds 1. Therefore, the investment of the Hephaestus cable-driven robot for CWM installation, based on the UK market, is projected to be economically acceptable and efficient. In particular, the investment of one Hephaestus cable-driven robot system could pay for itself in only 21.21 months when operated in the UK.

In accounting, the break-even point (BEP) refers to the point at which the total cost and total revenue are equal [25]. When adjusting the net cumulative cashflow to near zero in year 5, by adjusting the construction worker salary while keeping any other variables the same, it can be inferred that the investment of the Hephaestus cable-driven robot system will be worthwhile, in theory, if the local hourly wage for workers is higher than approximately 3.45 €/h. In other words, the proposed robot system for curtain wall installation task will be financially competitive in countries or regions where the median salary for a construction worker is above 3.45 €/h as of 2020, which is the BEP.

Furthermore, Table 4 demonstrates whether the Hephaestus cable-driven robot system is competitive in the G20 countries/regions (different currencies are converted to euros based on the exchange rates on 13 October 2020, according to Google). In this research, if the local median wage of construction workers is more than double the BEP, the investment will be defined as highly competitive; if the local median wage of construction workers is more than the BEP but less than double the BEP, it will be defined as competitive; otherwise, it will be considered as uncompetitive. Therefore, the table shows that the proposed system would currently be highly competitive, compared to the conventional method in most developed countries in the world, and it would be relatively competitive in many emerging economies as well, with a few exceptions such as Argentina, Brazil, China (mainland), India, Mexico, Russia, South Africa, and Turkey (according to www.salaryexpert.com as of October, 2020). However, as the economy continues to expand in these emerging markets and their average income of workers increases, it is predictable that the proposed system will become competitive in these countries as well in the near future.

Table 4. Median hourly rate of construction workers in G20 countries/regions, and indications on whether the robot is competitive in the respective country.

G20 Country or Region	Median Hourly Rate (in €)	Recommendation
Argentina	2.19 (198.68 ARS)	Uncompetitive
Australia	18.23 (29.93 AUD)	Highly competitive
Brazil	3.18 (21.07 BRL)	Uncompetitive
Canada	14.93 (23.23 CAD)	Highly competitive
China (mainland)	3.41 (27.25 CNY)	Uncompetitive
China (Hong Kong)	13.01 (118.60 HKD)	Highly competitive
France	14.15	Highly competitive
Germany	17.18	Highly competitive
India	1.15 (99.17 INR)	Uncompetitive
Indonesia	3.59 (62053.86 IDR)	Competitive
Italy	13.08	Highly competitive
Japan	14.66 (1826.55 JPY)	Highly competitive
Mexico	2.41 (60.66 MXN)	Uncompetitive
Russia	2.11 (192.16 RUB)	Uncompetitive
Saudi Arabia	8.69 (38.24 SAR)	Highly competitive
South Africa	3.12 (60.99 ZAR)	Uncompetitive
South Korea	10.18 (13,790.48 KRW)	Highly competitive
Turkey	2.51 (23,41 TRY)	Uncompetitive
United Kingdom	15.47 (14.05 GBP)	Highly competitive
United States	17.28 (20.29 USD)	Highly competitive

The results are important indicators for companies and policy makers in different countries and regions to decide whether the investment of the Hephaestus cable-driven robot is worth considering. Furthermore, as the manufacturing costs of the robot system drop and the global labor costs increase over time, it is foreseeable that the robot system will be competitive in even more countries worldwide.

6. Discussion

This research introduces a simple framework for economically evaluating single-task construction robots, based on a case study of a cable-driven curtain wall installation robot. The results indicate that the CDPR system in the case study is financially competitive in the UK, as well as in most developed countries or regions. The advantages and future validation of the methods, as well as the additional socioenvironmental implications, limitations, adaptability, and reproducibility, are further discussed in the sections below.

6.1. Advantages and Future Validation of the Methods

This paper mainly discusses the direct economic implications of STCR, using the proposed cable-driven robot for curtain wall installation as a case study. It will be one of the first CBA research instances focusing on STCRs, setting a valuable precedent for the field of construction robots.

The methodology is practical and helpful for the key beneficiary (e.g., the construction company) to make decisions about whether to invest in construction robots without acquiring large amounts of data. The calculation method is specifically designed to estimate the costs and benefits of an advanced solution for a specific task in a short amount of time.

Therefore, it does not require a large amount of time and effort of the key beneficiary, such as historical data collection and opinion survey.

Further, the proposed framework, as well as the results, can be further validated by the key beneficiary through a real-world pilot project in which the key performance indicators (KPIs) of the conventional and alternative scenarios (e.g., speed, performance, cost, etc.) can be more accurately measured.

6.2. Further Socioenvironmental Implications

The proposed methods mainly address the direct microeconomic evaluation of an STCR, compared to the traditional technique, through a simplified analyzing framework. However, more indirect socioenvironmental implications, other than productivity increase, are also worth noting. For instance, the STCR approach enhances labor safety. According to Eurostat, there were 3552 fatal accidents at work in EU-28 states during 2017, of which one fifth happened in the construction sector [26]. In other words, more than 700 accidental deaths took place within the construction industry in EU countries just in 2017. The reduction in the number of onsite construction workers at height, through applying construction robots, can substantially reduce the chance of fatal accidents and other injuries on the construction sites. Furthermore, the application of STCRs has a positive impact on construction quality through precise control and real-time monitoring, which potentially benefits the reputation and profitability of the relevant construction companies. Meanwhile, it also has a positive impact on resource consumption due to the precise automatic control system [2]. Moreover, the vacancy rate in the construction sector (excluding the real estate subsector) in the EU28 increased by 1.7% from 2010 to 2018, indicating growing labor shortages in the business. In particular, Germany observed 121,736 unfilled positions in the construction sector in 2018, compared to only 51,892 in 2010 [27]. The implementation of robots can help alleviate the growing labor shortages in the construction business. These aspects obviously make an even stronger case in favor of construction robots, although these additional socioenvironmental benefits are more difficult to monetize.

6.3. Limitations

Just like any other economic models, this initial CBA is by no means an impeccable process. The results reported in this section have certain limitations, summarized as follows.

1. The usability of the alternative scenario, currently based on a prototype, needs to be further tested and validated in real-world practice.
2. Many data for calculation are only rough estimations, and more accurate data might be possible in the future.
3. The manufacturing cost of the robot is only calculated based on prototyping cost in the EU market, thus cheaper alternatives, such as outsourcing, are not considered, and future mass production might be substantially lower.
4. Many long-term indirect socioenvironmental benefits are difficult to quantify and monetize. Also, the primary beneficiary in the case study is defined as the facade installation company. Therefore, the indirect socioenvironmental benefits are not included directly in the case study.

6.4. Adaptability and Reproducibility

As shown in previous sections, the case study provides a simple, but useful, tool to assess the benefit and cost of any given STCR system, which fills the gap in the economic evaluation of construction robots. The demonstrated process of CBA for STCR is highly adaptable and reproducible. Therefore, researchers, engineers, investors, and policy makers can easily follow and customize this method to assess the economic advantages of any STCR system, compared to traditional construction techniques and methods.

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A Cable Driven Parallel Robot with a Modular End Effector for the Installation of Curtain Wall Modules

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Abstract –

The installation of curtain wall modules (CWMs) is a risky activity carried out in the heights and often under unfavorable weather conditions. CWMs are heavy prefabricated walls that are lifted normally with bindings and cranes. High stability is needed while positioning in order not to damage the fragile CWMs. Moreover, this activity requires high precision while positioning brackets, the modules, and for that reason, intensive survey and marking are necessary. In order to avoid such inconveniences, there were experiences to install façade modules in automatic mode using robotic devices. In the research project HEPHAESTUS, a novel system has been developed in order to install CWMs automatically. The system consists of two sub-systems: a cable driven parallel robot (CDPR) and a set of robotic tools named as Modular End Effector (MEE). The platform of the CDPR hosts the MEE. This MEE performs the necessary tasks of installing the curtain wall modules. There are two main tasks that the CDPR and MEE need to achieve: first is the fixation of the brackets onto the concrete slab, and second is the picking and placing of the CWMs onto the brackets. The first integration of the aforementioned system was carried out in a controlled environment that resembled a building structure. The results of this first test show that there are minor deviations when positioning the CDPR platform. In future steps, the deviations will be compensated by the tools of the MEE and the installation of the CWM will be carried out with the required accuracy automatically.

Keywords –

Automation; On-site; Robotics; Facade

1 Introduction

The European construction sector constitutes an immense market. It is one of the main industrial employers in the European Union, contributing about 9% of its GDP, with an annual turnover of more than €1,500 million and a direct workforce of 18 million people [1]. Despite the fact that the construction sector is a fairly traditional sector, trends such as smart construction, involving advanced materials, innovative processes and concepts and green approaches, are becoming more noticeable.

The curtain wall modules (CWMs) are the building envelope technological system which represents the boundary condition between indoor and outdoor environment with the goal to guarantee and preserve the designed building performances. For this purpose, the as-built façade needs to guarantee the correct installation of the CWMs to achieve the performance assessed by project specs detailed in the design phase and validated with tests conducted under EN 13830. This critical but fundamental moment of installation phase requires a full accomplishment of operative instructions to guarantee the performance achievement with a strict accuracy of its component installation. Indeed, because the CWM setting is a millimetric activity due to the absolute position of façade, the installation process and regulations guarantee that the as-built façade corresponds to the design. For this reason, even if some mechanical regulations are possible through specific façade's components (bolts, screws, anchors), installers today have a central role. In addition to the installation operations to guarantee the correct setting of the CWM in line with project specs, other relevant issues related to site activities need to be managed such as risk control, preservation of the safety of personnel involved, and correct maintenance of the equipment used. The safety of personnel involved in all site activities (not only the one responsible for façade) is the most crucial aspect. The safety procedures are independent of specific building components, but related to general principles to be pursued for each activity during site operations based on national and local norms. In this frame, façade related risks (e.g., lifting materials, equipment placement, exclusion zones, falling restrain for personnel and material, weather condition during lifting operations) are some of the risks to be considered during CWM installation to preserve the safety operation of the site activities. In this scenario, to pursue the quality of installation while reducing its risk to preserve the site personnel's safety, automation through robot is an opportunity worth being investigated.

In order to cope with these issues, different robots for installing, painting, cleaning, delaminating, maintaining and inspecting any kind of facade were developed in the past. More specifically, several robotic devices have been classified for façade module installation [2]. Besides these single task robots, on-site factories like ABCS [3] and SMART [4, 5] developed techniques for installing fully prefabricated façade modules during the erection of new buildings. Apart from façade modules, there were experiences in on-site assembly of walls like in the Rocco project, in this case, for assembling building blocks [6]. Lee et al. [7] developed a robot on top of a platform that helps the human operator to handle a CWM. The most recent instance of the installation of a façade module with a robot dates to a manually operated robotic crane [8]. Test results show that in worst case the achieved repeatability of handler end-effector positioning is 7.0 mm. This result might not be sufficient for the installation of CWMs. Regarding the cable robots for installing façade elements, a tendon suspended platform robot was envisioned [9], but the definition degree of that solution did not show further detail, especially regarding the necessary cranes to support the loads and forces of the cables. Moreover, that solution did not show any type of on-board tools.

Cable-driven parallel robots (CDPR) are a subclass of parallel robots [10]. Instead of rigid links, they use cables to manipulate a mobile platform. The principle is to drive a mobile element in up to 6 degrees of freedom (DOF) by attaching cables to the mobile element and by synchronously controlling their length from a base frame with winches. At least 6 cables are required for controlling all 6 DOFs of the load, while often no more than 8 cables are used for better performance. The most well-known example of such robots is aerial cameras for stadiums [11] working with 3 DOF and 4 cables, and the first concept for manipulating all DOFs of a load dates back to the 1990s [12]. Today, they have already proven their benefits, in particular for large scale industrial applications [13, 14, 15]; indeed, the principle of a CDPR can be adapted to move heavy payloads over large dimensions. For the same reasons, CDPRs have being theorized in the past for several construction applications, from manipulating elements, contour crafting, to building inspection [9, 16].

In the HEPHAESTUS project, a redundantly constrained cable robot was built. The redundancy of using eight cables to control the six degrees of freedom of the platform increases the available workspace volume. Only few related works involving cable robots in the field of construction can be found. In [17], a concept for a cable robot for large-scale assembly of solar power plants is introduced. In [18], a cable robot concept for a contour crafting system is described. In [19, 20], cable-robots for automated brick laying can be found.

The work performed within the HEPHAESTUS project [21] features for the first time that a CDPR is designed, built and deployed specifically for the construction sector, with the primary purpose of installing CWMs, which encompasses two main tasks: bracket installation and module installation. The advantages of cable robots in HEPHAESTUS are their large workspace, high payloads, reconfigurability and modular components, which make it easily transportable.

2 Concept description

The aforementioned tasks (bracket installation and module placement) require high relative and absolute accuracy. To accomplish such accuracy, it is necessary to foresee the precision of the CDPR, which was estimated to have a tolerance of 40 mm [22] in previous phases. Therefore, in previous stages of the project, it was foreseen that there would be two means for installing the CWM: the CDPR for the rough positioning and the Modular End Effector (MEE) along with its tools for the fine positioning.

2.1 CDPR

From a geometrical point of view, a CDPR is an association of cables of variable lengths linking a drawing point attached to base frame, and a fixing point attached to the mobile element or platform. How these drawing and fixing points are positioned in space, respectively in the general frame and the mobile platform frame, and how they are connected together formulate a configuration.

2.1.1 CDPR calculation

The geometrical design of the CDPR presented in Figure 1 can be summarized as the definition of the following parameters: (i) number of cables, (ii) geometry of the structure, (iii) geometry of the platform, and (iv) cable configuration. Based on previous studies indicating that CDPRs driven by eight cables have appropriate performances [23], this number of cables was chosen. The parameters (ii) and (iii) are defined by the positions of the drawing points and attachment points respectively (see Figure 1). The cable configuration (iv) defines the pairs of drawing and attachment points that are connected by cables. Therefore, significant efforts in the design of this CDPR were dedicated to the definition of an appropriate set of parameters (ii), (iii) and (iv).

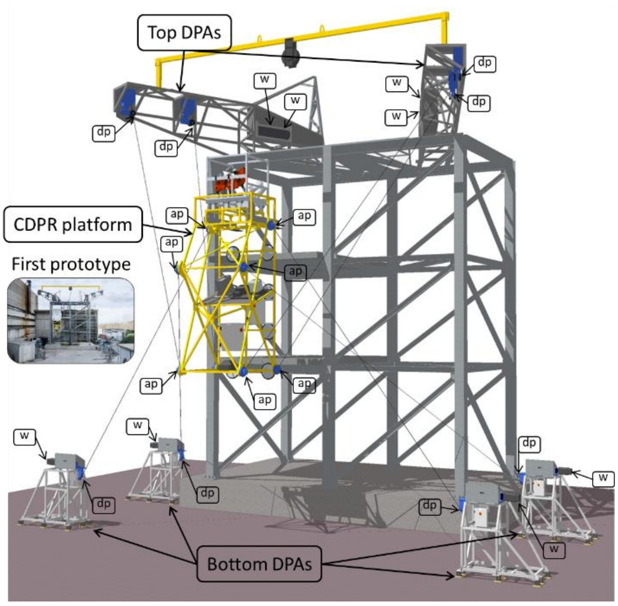

Figure 1. Hephaestus CDPR prototype

The abstract goal of finding an appropriate set of parameters was formulated as an optimization problem. The cost function of the proposed optimization problem is the maximal cable tension, directly linked to the Safe Working Load (SWL), obtained during operation across the building facade. The choice of this cost function is motivated by the direct relationship between the SWL and the cost of the machine. Minimizing the SWL leads to minimizing the maximal loads that are applied on the mechanical parts of the CDPR and, therefore, the cost is minimized. In addition, the constraints of the optimization problem include the positioning accuracy which should meet the precision necessary for the installation of the CWMs. Further details on the geometrical optimization of the Hephaestus CDPR prototype can be found in [24].

2.1.2 CDPR hardware

The Hephaestus CDPR is composed of 7 subassemblies. The first set of subassemblies provides the means of controlling the lengths of the cables. These subassemblies are fixed to the building, which works as the base frame for the robot. They are called drawing point assemblies (DPA in Figure 1) and come in two types. The first type is fixed at ground level, materializing the lower drawing points (dp in Figure 1) of the proposed configuration (one per assembly). The second type is attached to the building top slab. Each top DPA materializes two among the top drawing points. There are, therefore, two top DPAs and 4 bottom DPAs (see Figure 1).

Each drawing point need a winch, a swivel pulley at the location of the drawing point, and a force sensor for monitoring the cable tension. The components are the same for all drawing points. The travelling sheave winches (VICINAY winches WB21.L30S.1: SWL 15.7 kN, drum torque 2128 Nm, velocity 30 m/min, cable travel 16m, see w in Figure 1 and Figure 2) are powered by a servomotor with brake and absolute multi-turn encoder integrated, associated to a gearbox and wire rope spooling mechanism synchronized with the grooved drum.

The swivel pulley installed at the theoretical location of the drawing point rotates around a vertical axis; it guides the cable towards the matching fixing point. The force sensor is embedded in the shaft of the sheave directing the cable from the winch to the swivel pulley. The steel wire rope is a Ø11mm non-rotating cable with a minimum breaking load of 115.5 kN.

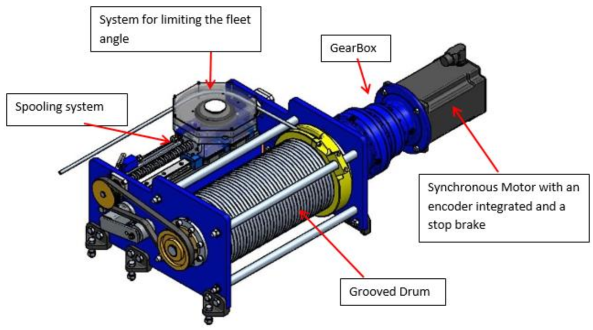

Figure 2. CAD view of the VICINAY Winch WB21.L.30S.1

The mechanical structure of the DPAs is designed in order to transfer the load from the swivel pulleys and the winches to the anchoring elements. They were designed to show a displacement of less than 50 mm at the drawing point location when loaded with the winches' SWL. Steel anchorage plates are embedded during the construction of the concrete building in the third (top) slab. The supporting structures are later welded to these anchorage plates in the correct position so that the DPA are in the correct coordinates with the required tolerances, with the drawing point positions being monitored continuously by a surveyor with a total station

Another CDPR subassembly is the platform (see Figure 1 and Figure 5). It features the 8 fixing points placed accordingly to the dimensions set in the configuration, as well as the various tools and power systems for the MEE. The total weight of the fully loaded platform reaches 1460 kg, in which 350 kg accounts for the carried CWM.

The norms applied during the design are ISO 4301, ISO 16625 and FEM 1.001. All elements have been designed with a safety factor of at least 5.6 in order to match the M5 mechanism group requirements.

The final CDPR subassembly is a weatherproof electrical cabinet housing the central control unit. It features the servomotor drives, the associated power units, the central PLC where the central control is implemented, and the associated inputs and outputs acquisition system. The cables towards the platform (data and power) are directed to it by means of a cable chain mechanism fixed to a beam installed between the two top DPAs.

2.2 MEE and its components

The MEE is the set of tools that performs each of the activities necessary for installing the CWM onto the structure of the building. The MEE is fixed to the CDPR platform (see Figure 5). In the case of the HEPHAESTUS project, two main activities need to be performed. First, there is the fixation of the bracket onto the concrete slab. This task is achieved by a robotic arm. Second, there is a placement of the CWM modules onto the brackets. This task is achieved by a vacuum system attached to the CDPR platform that picks a CWM from an inclined magazine and releases the CWM when it is placed onto the brackets.

2.2.1 Robotic arm and its tools

Selected tools need to be manipulated by the robot in order to mount brackets to hold the CWM to the building. The most versatile method is in-situ mounting and this was the chosen approach in this project. The list of actions needed to be handled by the robot is concluded: drilling of holes for anchor bolts, picking and placement of bracket over holes, picking and placement of anchor bolts in holes, setting of bolts into holes, and tightening of anchor bolts nuts to set torque. A Universal Robots UR10e was selected as the tool manipulator. This was done based on previous experience with this robot and its possibilities and limitations, specifically regarding drilling in concrete. The robot arm also allows for excellent adaptability to changes based on underway project learnings. The arm was mounted on a custom structure made of profiled aluminum bars. A tool-changer system was integrated to give the robotic arm the possibility to manipulate a variety of tools.

Four tools were put together to achieve the needed customized functionality: 1) the drilling tool, 2) the bracket picker and holder, 3) the setting tool with a hammer function, and 4) a tool to torque the nut of the anchor.

The cycle is completed by the robotic arm returning to the bracket holder, and releasing the vacuum and magnets from the slab and bracket correspondingly, before the bracket holder is returned to the tool dock.^

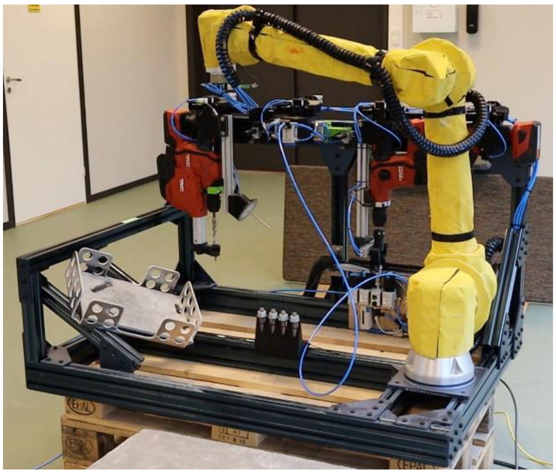

Figure 3. Robotic arm and its tools before mounting on the CDPR platform.

2.2.2 Stabilizer of the robot's frame

One of the issues regarding the accuracy of the robotic arm relied on the stability of the frame that hosts the robotic arm and its tools while performing tasks.

For achieving such needs, a linear system with vacuum cups was defined, tested and prototyped. This linear system was conceived for hosting forces of up to 1500N.

Figure 4. Stabilizer of the robot's frame prototype during the opening of the stabilizers.

The linear system consisted on two subsystems: the linear actuators and the machined steel profiles (see Figure 4) that run along the rails with the help of carriers.

2.2.3 Vacuum Lifting System for picking and placing the CWM

The Vacuum Lifting System (VLS) is capable for picking and placing the CWM of 350kg during operations that require inclined plans.

The VLS is designed to grip, in vertical position, a CWM of the aforementioned mass, with a smooth glass surface, and a surface A_{zx} of 5.1m² . The CWM is a parallelepiped with three different faces $A\,(A_{yz}, A_{zx}, A_{xy})$ perpendicular to x, y, z axes with values $A = (0.68 \quad 5.1 \quad 0.3)^T m^2$ and showing a maximum aerodynamic coefficient c_a at 1.32. It would be possible to work in both dry and wet states, without ice, with the friction coefficient being estimated 0.2 (μ in *(3)*). The VLS is dimensioned to lift a load greater than or equal to twice its design load with the minimum relative vacuum pressure q_r. Finally, the altitude should be at least 900m from sea level, the temperature between -5 to 40 ºC, and accordingly the wind pressure q_w during service is estimated lower than 125N/m² and the vacuum differential pressure q_r at least equal to 600 mbar. The system creates a grip force f_g between the surfaces of the CWM and those of the $n = 8$ suction cups, showing a diameter d of Ø360 mm. The total load solicitation vector $\boldsymbol{s}$ is the sum of: the CWM mass m multiplied by gravity vector g, and by acceleration $j = (1\ 1\ 1)$ m/s² due to the movement, and the forces due to the wind action f_w, each factorized with the applicable partial safety coefficients ($\gamma_p = 1.1$), which are expressed as follows:

$$f_g = n\frac{\pi \cdot d^2 \cdot q_r}{4} = 48.86\ kN \quad (1)$$

$$f_w = c_a \cdot q_w A = (112 \quad 841 \quad 50)^T N \quad (2)$$

$$s = \left(\frac{m(g+j)}{\mu \cdot (1\ \ 1\ \ 1)^T} + \frac{\gamma_p \cdot f_w}{(\mu \quad 1 \quad \mu)^T}\right) = \begin{pmatrix} 2.52 \\ 2.52 \\ 20.8 \end{pmatrix} kN \quad (3)$$

The current VLS design is validated by f_g being greater than twice any component of $\boldsymbol{s}$.

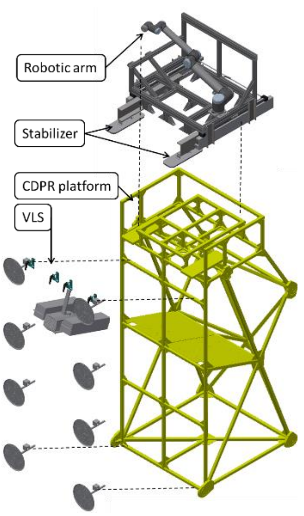

Figure 5. location of the MEE on the platform.

The VLS, and its warnings and safety measures are connected to the Beckhoff control and therefore it can be activated automatically as explained in the next section.

2.3 Control system

In Figure 6, the scheme of the hardware and wiring of the HEPHAESTUS robot is shown. The system consists of 4 PCs in total. Starting from the left side in the scheme, a standard PC is used to execute a software tool to automate the façade panel installation. This tool commands the steps in the correct order to mount the facade modules. Furthermore, it provides a GUI for the operator to control the whole HEPHAESTUS robot. It is connected to a total station via TCP/IP, which can measure the absolute pose of the cable robot platform and to the IPC on which the cable robot controller is running. The cable robot controller is based on the TwinCAT 3 software from BECKHOFF [25]. It consists of a soft-PLC and a motion controller. The latter can either be a Beckhoff CNC, or an advanced motion controller. The IPC is connected via WLAN (CANopen) to the Radio Control, via Ethernet (EtherCAT) to the safety sensors, I/Os, force sensors and drives.

Furthermore, the IPC has an Ethernet (EtherCAT) interface to the IPC of the MEE, which is integrated within the EtherCAT network as an EtherCAT slave. On the MEE IPC a PLC is implemented to control the MEE system consisting of the ROS-PC to control the UR-Robot, the stabilizer, and the vacuum system.

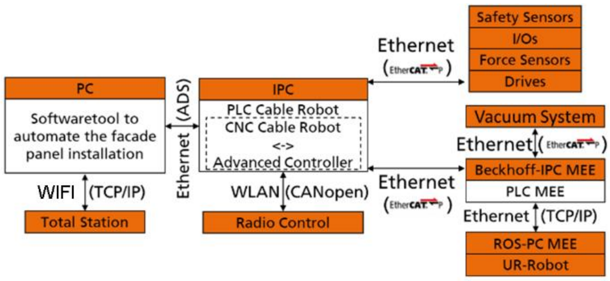

Figure 6. Scheme of the hardware and wiring of the HEPHAESTUS cable robot.

The main application controls the interactions between the user and the main controller. The application UI shows cable robot data, such as cable tensions, and each state the robot is performing in real time. It also allows the user to intercept each state, pausing the operation, or to stop the task. It is connected to the cable robot controller, allowing the user to move the cable robot and see the state the cable robot and the MEE are in at any moment, allowing the user to operate and control it, and the total station controller, allowing the user to obtain position and rotation measures at will.

A precise kinematic model is necessary in order to guarantee a satisfying positioning accuracy of the CDPR. Since the pose of the platform is computed based on the winch motor positions, cable sagging and elongation may be considered [26]. Among other aspects related to the position tracking control for CDPRs, these are still ongoing research subjects addressed in this project.

2.4 State Machine

The main controller is designed to operate as a state machine that controls all the individual controllers. Likewise, it is designed to work separately from the UI, merging the real time environment with the UI thread, and it controls all the error controllers to broadcast individual error signals. There are two main operations that the robot must do in order to complete the CWM installation successfully: first drill and set the brackets in the correct positions, and then set the CWMs in the corresponding brackets. To do both of them there are several states that the controller must follow, each one of them linked to a specific controller (cable robot control, MEE control or total station control). Each state, as shown in the simplified state machine diagram (see Figure 7), has an optional breakpoint where the user can stop the operation if a malfunction is detected. Besides these two main operations, the state machine contains also the semi-automatic initialization states of the total station.

3 Prototyping and tests

The first demonstration tests were performed in TECNALIA facilities in Derio, Basque Country (Spain). Once all the components of the demonstrator were installed, the operation of all the components (motors, movement of the robot, positioning in relation with the steel structure, sensor, etc.) was verified. This was the first time the different elements of the robot (winches with cable pulling on the platform/base) and the higher-level control of the robot that makes the coordination of the winches were put together.

3.1 Building structure used for the demonstration

For this purpose, a steel structure has been erected matching the foreseen dimensions of the demonstration building: 10.2m high, 8.80m wide, and 2.7m deep. Two concrete slabs have been installed at the first and second floor to perform all tests required for installing one CWM.

The steel structure has features to accommodate the top DPAs on the top floor; the bottom DPAs are directly anchored to the ground (Figure 1).

The higher platform empty weight more than expected and the SWL lower than originally planned (respectively 1110 kg instead of 910 and 15.7kN instead of 20) led to the nominal transit positions of the top row of panels not being accessible. The transit distance for the top floor panels therefore needed to be reduced from 600 to 450 mm.

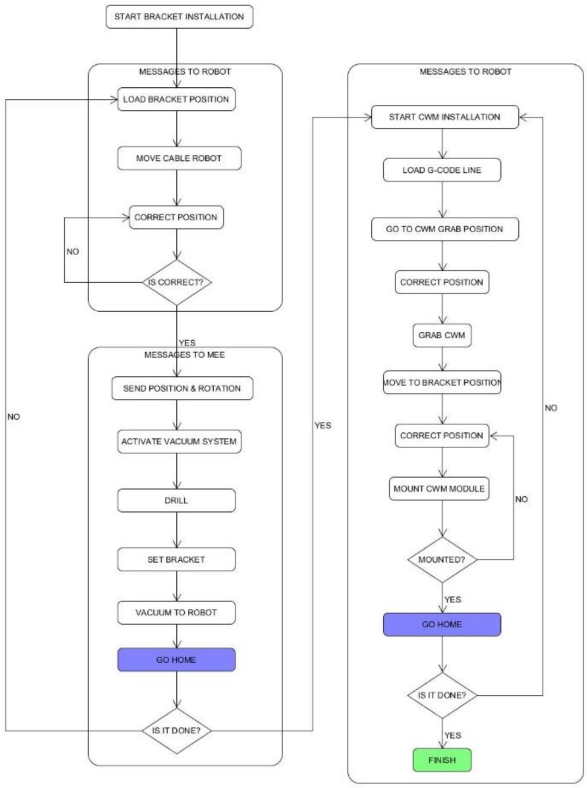

Figure 7. Simplified state machine diagram

3.2 Installation of the CDPR

After the erection of the building, the DPAs, mobile platform and control cabinet were brought to the building site. The top DPAs (2500kg each) were installed on the building top floor by the means of a mobile crane. The bottom DPAs (1100kg each) can be moved around using a forklift. Once the DPAs have been installed, calibration must be carried out.

Calibration of the drawing point positions is performed thanks to the integration of total station targets onto the swivel pulley assemblies. Each swivel pulley assembly features 4 targets; their positions are used to build a local frame to reconstruct the current position of the associated drawing point. In order to calibrate the full system, apart from the A and B points, there are 3 Leica 360º targets [27] attached to the cable robot platform in order to track it on the move, 3 Leica 20x20 mm reflectors attached to the cable robot platform in order to calibrate the origin point of the MEE with respect to the cable robot platform frame, and at least 3 Leica 20x20 mm reflectors to triangulate the building from the total station. It is highly advisable to calibrate all the prism and reflectors at the same time to achieve best possible accuracy.

The calibration procedure has been performed at the same time as the installation of the DPAs, with the drawing point positions being monitored continuously by a surveyor with a total station. The objective was to have the DPAs installed as close as possible to their theoretical positions: the distance to the theoretical positions was measured at maximum 19mm.

3.3 Results

The first results of the demonstration show a better performance than expected in previous phases of the research project (see Figure 8 and check video in [21]). The maximum position error of the CDPR is about 20mm and the max orientation error about 0.8deg. Moreover, the preliminary results show a promising repeatability (with an accuracy of 1-2 mm) of the CDPR while moving the platform within the workspace. However, more tests are necessary to define better this parameter. The deviations in respect to the desired position were supposed to be adjusted by the MEE while fixing the brackets. However, due to time constrains during the installation of the CDPR and the MEE, some calibration issues appeared and the transformed of the MEE with regard to the 0,0,0 point of the building was not achieved properly. For that reason, some deviations occurred during the placement of the bracket. This is a topic that will be improved in the next phase.

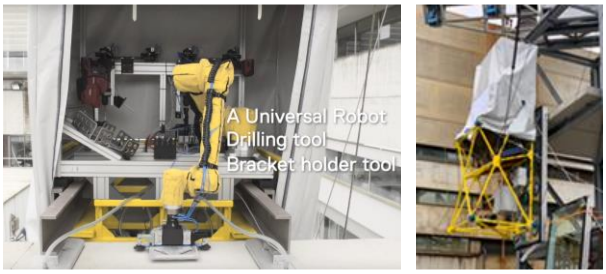

Figure 8. MEE and CDPR in operation as in [21]

4 Conclusions and future work

The first test of a CDPR for installing CWMs was achieved with better than expected results. However, there are still some points that need to be improved:

- Improve the calibration of the MEE in regards with the building in order to achieve a better accuracy.
- The detection of the CWM while it stands on the magazine and measuring its location.
- Detection of the brackets that are already fixed on the building slab in order to adjust, if necessary, the CDPR path while placing the CWM.

In order to seek for future commercialization, a market research was carried out which found a growing awareness from building owners and residents about comfort and health as well as political and economic drivers (e.g: nZEB and other EU directives, incentive schemes and favorable tax regimes, especially for green construction). Technological innovations will complete these drivers, making investors, policymakers and professionals (i.e. architects, designers as well as façade manufacturers) accelerate the adoption of construction robots. Therefore, the goal is that in the coming years the innovations mentioned in this paper will reach the market with the following exploitable results: i) CDPR for vertical works: suitable for handling, moving and placing CWMs; ii) MEE: including several tools to automate the insertion of a connector onto the building´s structure; iii) curtain wall adapted to robotic installation: for fixing elements of the CWM to slab; CWM to bracket; and connection between CWMs; and iv) Hephaestus system: as an integrated solution for handling and installing CWMs. To facilitate commercialization of new device categories, standards can do the following:

1. Standardize the components and interfaces from which it is made in order to allow for faster development and efficient supply chains ("interoperability").
2. Standardize the processes and infrastructures surrounding the new technology or product/service.
3. Ensure quality and efficiency of the technology and/or its development processes in order to minimize the risks for the involved stakeholders.

During a final demonstration stage of the project, the robot will complete the installation of a set of CWMs covering part of the façade of a demo building particularly built and enabled for these activities. This demo building has been erected in the machinery park owned by ACCIONA and is located in Noblejas, Toledo (Spain), so that the performance of the cable robot can be demonstrated in a real construction environment. The emo building was erected with three floors and a total height of 10.2 m, and the façade is 8.5m wide. To access the various floors of the demo building during demonstration activities, a staircase has been installed on the back side of the building where no facade panels will be installed. The Hephaestus system will be validated, among other performance indicators, in terms of time required to complete the operations for the CWM placing, the accuracy, the efficiency and the usability for workers of the construction sector. Also, special care will be taken in order to fulfil the safety requirements and recommendations for these robotic operations.

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