Assessing the wider impact of fully autonomous equipment for earthworks and land remediation projects.

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Abstract

The deployment of fully autonomous construction equipment for earthworks has gained significant interest in both academia and industry. This is driven by rapid advancements in artificial intelligence skilled labour shortages and the need to drive efficiency, safety and productivity. Despite successful trials, questions remain about their wider impact on the sector. This study seeks to investigate the wider potential impact of fully autonomous earthwork equipment in the sector. A qualitative approach using a case study of an earthworks and land remediation project was adopted with data gathered through project documentation and semi-structured interviews. Data analysis involved scope, operation, cost and resource analysis of project documentation and thematic analysis of the interview transcripts. A potential for between 50% - 59% programme squeeze and 24% - 32% labour cost savings is revealed as achievable for four illustrative scenarios using the case study project as a baseline. Participants acknowledged efficiency and safety benefits but raised cultural resistance, technology limitations for complex site conditions, high upfront investment and job displacement as concerns. This suggests that whilst full automation can offer significant efficiency gains for earthworks, a balanced and ethical approach to implementation that prioritises human augmentation rather than replacement of human roles to preserve the social value contributions of the sector will be required.

Keywords–
Artificial intelligence, automation, autonomous construction equipment, earthworks, productivity

1 Introduction

The earth moving sector of the construction industry has been a pioneer in the adoption of automation-related technologies for equipment due to the potential to reduce operational cost, improve productivity and enhance safety [1]. These automation-related technologies include computer vision-based equipment monitoring, GPS location and interlinked information technologies for automated machine guidance and control [2]. Some of the existing research efforts have focused on the development of technical systems for autonomous navigation and control of the equipment [2], [3], [4], stakeholder participation in the development of open-source software for model-based autonomous construction machinery [5], and the safety aspect of deploying fully autonomous equipment on construction sites [6].

Advances in artificial intelligence (AI) offer opportunities for achieving fully autonomous systems. Hancock [7] defined automated systems as those designed to accomplish a specific set of largely deterministic steps in a repeating pattern to achieve a limited set of pre-defined outcomes. In contrast, autonomous systems are generative, can learn, evolve and permanently change their functional capacities using operational and contextual information inputs [7]. The growing shift in focus from semi-automation to full unmanned autonomy [4], [8], [9], [10], [11] is driven by the need to tackle skilled labour shortages whilst also achieving productivity gains. Current studies on the productivity impact of automation-related technologies, especially in the earthworks sector have predominantly focused on semi-autonomous operation [12], [13] rather than full unmanned autonomous operation which can have significant socio-economic ramifications. Even then, these studies tend to be limited to the productivity benefits of semi-automation without considering the wider socio-economic impact.

Furthermore, current trials of full unmanned autonomous deployment have been dominated by a focus on the technical systems for executing single earthwork operations [8], [9], [10], [11] rather than large scale earthworks and land remediation schemes. This raises the need to further interrogate the wider impact full autonomous deployment not just from a productivity or technical solution perspective but also the ethics of worker replacement and other socio-economic impacts.

The aim of this study was therefore to evaluate the wider impact of fully autonomous machinery and equipment in the earthworks and land remediation sector, including the perspectives and attitudes of professionals in this sector towards full automation.

To achieve this, the next section provides some discussion on current developments in the automation of heavy-duty construction equipment and its impact. This is followed by a discussion of the research methodology, the findings and discussion, and then the conclusion.

2 Automation of Heavy-Duty Construction Equipment and its Impact

Automated machine guidance and control products have been introduced into heavy-duty construction equipment (shown in Table 1). Automated machine guidance and control using real-time kinematic (RTK) GPS antennas enable machine operators' complete tasks quicker and with more precision [1].

Table 1. Heavy duty construction equipment for earthworks

Equipment and example of a typical specification	Example image
Excavator e.g., Komatsu 36T Excavator with GPS equipment (KOM PC 360 + GPS)	
Articulated Dump Truck e.g., Komatsu HM300 Articulated Dump Truck (KOM HM 300)	
Bulldozer e.g., Komatsu D65PX Bulldozer with GPS equipment (D65PX + GPS)	
Compaction Roller e.g., CAT 13T Compaction Roller (CAT CS66B)	

Advancements in artificial intelligence (AI) and other related information technology systems has led to an increased focus on moving from partial to full unmanned automation. Tan [8] focused on the development and testing of an unmanned compactor roller using a visual Simultaneous Localization and Mapping (SLAM) algorithm. This system was developed by retrofitting a conventional roller with stereo cameras and industrial computers (ZED binocular camera, NVIDIA development board) to achieve real-time positioning and trajectory planning. Laboratory testing results revealed that the SLAM algorithm could enable the roller work autonomously within an acceptable range of error. Whilst full automation for bulldozers remains relatively low, Peng et al., [10] successfully developed and tested an integrated intelligent autonomous driving bulldozer system developed with Global Navigation Satellite System, inertial measurement unit, visual cameras, and light detection and ranging (LiDAR).

Excavators have also been tested for unmanned operation. Zhang [9] developed an automated excavator system for material loading using multimodal perception sensors, LiDAR and cameras with advanced image enhancement, material and texture classification, and object detection algorithms. Experimental and real-world testing was successful but revealed challenges from terrain differences, noisy sensor readings and hardware sensor failures in the real-life scenarios. Jud et al., [4] also developed an autonomous walking excavator (HEAP) that was successfully deployed for excavation, dry stone wall assembly, and forestry work, with some stability and control challenges detected depending on the terrain and ground conditions. A fully automated excavator was also trialled in the UK for trench excavation by retrofitting a conventional Yanmar SV100-7 to enable it to operate autonomously using prerecorded points to dig georeferenced trenches (see Figure 1) [11].

Figure 1: Bespoke AI operated Yanmar SV100-7 excavator trial trench dig in Manchester, U.K [11]

Previous studies on the impact of automation in the earthmoving sector relate mostly to semi-automation rather than full unmanned automation. A discrete simulation study by Shehata et al. [12] showed productivity improvement of 41.47% resulting from use of GPS-based automated machine guidance and control. Another field study by Azar et al., [13] revealed productivity improvements of between 6% to 34% for bulldozers and between 19% to 23% for excavators resulting from GPS-based automated machine guidance systems. The relative dearth of studies evaluating the wider impact of full automation for earthworks in construction is not surprising given that these are still mostly in their development and trial stages. Also, whilst any level of automation in construction can have some productivity benefits, exactly how these benefits translate to all stakeholders and how to overcome the negative impact can be unclear [14]. Thus, as fully unmanned automation gets closer to reality for earthworks equipment, it is important to interrogate the wider productivity and socio-economic impact as well as implementation challenges, which is what this study seeks to undertake.

3 Research Methodology

A qualitative approach and single case study design with embedded units of analysis was adopted for the study as shown in Figure 2. The single case study, referred to as Project A was of an earthworks re-engineering and land remediation of a brownfield redevelopment scheme in Wales, U.K. Project A involved 5 elements of works with equipment operated by 5 gangs totalling 38 equipment operators (see Table 2) with the total value of the works, including preliminaries, pre-construction design, and overheads estimated at £12,000,000. These 5 work elements were analysed as embedded units in Project Case A. Data collection began with the gathering of relevant project documentation (project programme, project scope, cost, resource schedule and operational delivery) for analysis to establish the "as is" baseline for project A in terms of percentage cost for labour, plant and fuel costs. This was followed by an illustrative scenario analysis of replacing human-operated equipment with fully autonomous equipment for all the tasks, which was compared against the "as-is" baseline for Project A. This was to determine potential programme squeeze and cost impact. Semi-structured interviews were then conducted with 6 experienced managers and professionals involved in Project A (see Table 3). The participants were purposively sampled because of their involvement in project A as well as their experience on earthworks and land remediation projects.

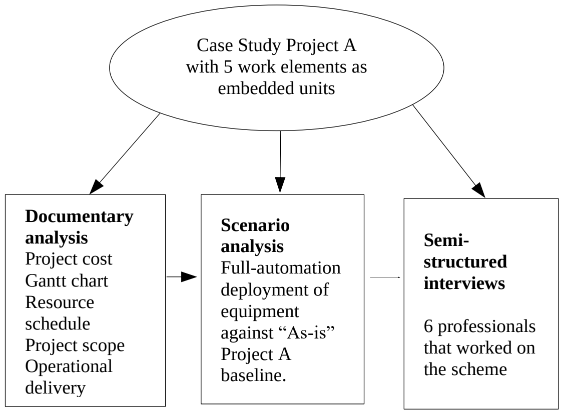

Figure 2: Research design adopted for the study

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Table 1. Elements of work and allocated equipment for Case Study Project A.

Gang	Element of works	Equipment operated by Gang
Gang 1 (6 operators)	Trial pitting and investigatory works: Total area = 909,112m2	1 KOM PC 360 + GPS Excavator, 3 KOM HM 300 ADTs, 1 D65PX + GPS Dozer, 1 CAT CS 66B Roller
Gang 2 (6 operators)	Treatment and control measures	1 KOM PC 360 + GPS Excavator, 3 KOM HM 300 ADTs, 1 D65PX + GPS Dozer, 1 CAT CS 66B Roller
Gang 3 (10 operators)	Re-engineering lakes and reens: involved excavation of 230,763m3 and formation of permanent watercourses to existing plot levels.	2 KOM PC 490 LC Excavators, 6 KOM HM 300 ADTs, 1 D65PX + GPS Dozer, 1 CAT CS 66B Roller
Gang 4 (8 operators)	Commercial area remediation	1 KOM PC 360 + GPS Excavator, 5 KOM HM 300 ADTs, 1 D65PX + GPS Dozer, 1 CAT CS 66B Roller
Gang 5 (8 operators)	Bulk earthworks (Phase 1&2): Phase 1 = 842,081m3 of earthworks Phase 2 = 802,421 m3 of earthworks	1 KOM PC 360 + GPS Excavator, 5 KOM HM 300 ADTs, 1 D65PX + GPS Dozer, 1 CAT CS 66B Roller

Table 3. Interviewee experience and specialism matrix

No.	Interviewee position	Sector specialism	Experience (years)		
			5-15	15-20	20+
1	Director / Partner (Commercial Background)	Building			✓
2	Operations Manager	Earthworks and remediation		✓	

3	Senior Works Manager	Earthworks and remediation		✓
4	Site Manager	Civil Engineering	✓	
5	Works Manager	Civil Engineering	✓	
6	Senior Quantity Surveyor	Civil Engineering & Earthworks and remediation	✓	

The interviews were conducted in-person and delved deeper into perceptions and attitudes towards unmanned full autonomous equipment for the earthworks and land remediation using Project A as the context, the potential return on investment from deploying this equipment if it became a reality, and the barriers and limitation associated their use. This semi-structured interview data was transcribed and analysed using a thematic analysis process to generate the findings.

4 Findings and Discussion

The UK working time directive specifies a maximum of no more than 48 hours a week on average. Based on the actual hours worked on Project A, with 9.5 hours worked each day the limit of the legislation was pushed as far as reasonably possible to 47.5 hours worked each week. The scope of activities for all five elements of work undertaken by the equipment operator gang 1-5 have been specified in Table 2. These are presented in Table 4-8. The treatment and control measures involved operators using the equipment to prepare the area ready for a treatment and control plant to be built and commissioned. The works undertaken to cut and re-engineer the lakes and reens involved operators using the equipment to cut and fill, with on-site sourced material to safely achieve the profile within the design information. The lakes and reens of the site form a natural flowing watercourse and drainage system for the plots of residential and commercial land. The works undertaken for the commercial area remediation involved equipment operators using on-site sourced uncontaminated and adequate material to re-engineer the ground back to an acceptable level and condition. The main earthworks involved operators use of adequate on-site sourced load-bearing material to re-engineer the ground back to an acceptable level and condition.

Table 4: Scope of activities and cost and duration for works undertaken by Gang 1

Element of works	Sub-activities	Total Duration
Trial pitting and investigatory works	1) Plot and set-out grid of trial pits to be dug; 2) Mobilise excavator to site and begin digging trial pit; 3) Load arisings into Articulated Dump Truck (ADT) to acceptable level; 4) With ADT, cart the arisings from point of excavation to the defined point of disposal (on site stockpile); 5) Return ADT to point of excavation, or to the next trial pit; 6) Repeat steps 2 to 5 until all trial pits are complete; 7) Sampling is taken from bottom of the pit, or from the arisings; 8) Once sampling is complete, mobilise excavator to on-site stockpile; 9) Load previously stockpiled material into ADT.	50 workdays @9.5 hours a day = 475 hours

Table 5: Scope of activities and cost and duration for works undertaken by Gang 2

Element of works	Sub-activities	Total Duration
Treatment and control measures	1) With the GPS enabled excavator set up to start initial excavations; 2) Excavate contaminated material and load into ADT; 3) With ADT, cart material away for segregation into defined bio-pad or stockpile; 4) Once contaminated material is removed as far as is necessary, ground re-engineering commences; 5) With an excavator adequate, load-bearing granular material is loaded from on-site stockpile into ADT; 6) With ADT, cart material to 'Wier and Settlement Pond' work face 7) With roller and excavator, shape and compact material in repetitive layers until the digital model of the 'Wier and Settlement Pond' is complete.	70 workdays @9.5 hours per day = 665 hours

Table 6: Scope of activities and cost and duration for works undertaken by Gang 3

Element of works	Sub-activities	Total Duration
Re-engineering lakes and reens	1) Plot and set out with site engineer the line and levels to which excavations are to be carried out; 2) Excavate surplus material and load into ADT; 3) With ADT, cart material away to defined stockpile; 4) Return ADT to work face, repeat steps 2 to 4 until surplus material is removed; 5) With an excavator load adequate, load-bearing granular material from on-site stockpile into ADT 6) With ADT, cart material to 'Lakes and Reens' work face 7) With roller and excavator, shape and compact material in repetitive layers until the guidance from engineer is met and the 'Lakes and Reens' are complete.	52 workdays @ 9.5 hours per day = 474 hours

Table 7: Scope of activities and cost and duration for works undertaken by Gang 4

Element of works	Sub-activities	Total Duration
Commercial area remediation	1) With the GPS enabled excavator set up to start initial excavations including further localised trial pitting; 2) Excavate contaminated material or vegetation and load into ADT; 3) With ADT, cart material away for segregation into defined bio-pad or stockpile ready for others to undertake specialist stabilisation activities; 4) Once contaminated material is removed as far as is necessary, ground re-engineering commences; 5) With an excavator adequate, load-bearing granular material is loaded from on-site stockpile into ADT; 6) With ADT, cart material to 'Commercial Area' work face; 7) With roller and excavator, shape and compact material in repetitive layers until the digital model of the 'Commercial Area is complete.	200 workdays @9.5 hours per day = 1900 hours

Table 8: Scope of activities and cost and duration for works undertaken by Gang 5

Element of works	Sub-activities	Total Duration
Bulk earthworks	1) With the GPS enabled excavator, set up to start initial excavations from areas in need of cut; 2) Excavate material and load into ADT; 3) With ADT, cart material away to area of fill and unload; 4) Return ADT back to excavator in area of cut 5) Spread material with dozer; 6) With a compaction roller repetitively compact in acceptable layers; 7) Repeat steps 2 – 6 until the digital model loaded is complete	289 workdays @9.5 hours per day = 2,745.5 hours

Table 9: Cost analysis breakdown for work elements in Project A

Gang	Work element	Labour (L)	Equipment hire (E)	Fuel (F)	Total cost per work element (L+E+F)
1	Trial pitting	£60,325.00	£67,000.00	£46,084.50	£173,409.50
2	Treatment and control measures	£84,455.00	£93,800.00	£64,518.30	£242,773.30
3	Lakes and reen re-engineering	£103,987.00	£129,480.00	£53,529.84	£286,996.84
4	Commercial area remediation	£317,300.00	£394,000.00	£205,884.00	£917,184.00
5	Bulk earthworks	£458,498.50	£569,330.00	£528,547.32	£1,556,375.82
	Total cost	£1,024,565.50	£1,253,610.00	£898,563.96	£3,176,739.46
	Percentage of overall cost	32.25%	39.46%	28.29%	

The findings from the cost analysis (Table 9) reveal that 32% of the actual cost of activities for all five work elements was for labour i.e., the 38 skilled equipment operators. The other 40% represented plant hire costs whilst 28% represented the fuel costs.

4.1 Potential programme and cost benefits

Four illustrative full automation deployment scenarios were analysed against the Project A baseline parameters to evaluate potential programme and cost impact as shown in Table 10. All four scenarios assume that that the equipment hire cost for the fully autonomous equipment will be the same as that for the conventional equipment used in Project A, and that the fully autonomous equipment would follow the same work execution steps specified in Table 4-8 with the same performance outputs for the work elements.

Table 10: Comparison of Project A baseline against deployment scenarios

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Hours per shift	9.5-hour shift	23-hour shift	19-hour shift (2 x 9.5-hour shift)	9.5-hour shift	9.5-hour shift
Operators per day	38	1	10	1	5
Programme (days)	661	273	331	661	661
Labour cost	£1,024,565.50	£26,962.25	£269,622.50	£26,962.25	£134,811.25
Total cost	£3,176,739.46	£2,179,136.21	£2,421,796.46	£2,179,136.21	£2,286,985.21
Project cost savings		31.40%	23.76%	31.40%	28.01%
Programme squeeze		58.70%	50%	0%	0%

Deployment scenario 1, which is in line with previous arguments that the automation of unmanned equipment will mean they can operate 24 hours/day, hence extending working hours [10]. 23 hours unmanned equipment working time was used for this scenario, allowing 1 hour per day for refuelling and minor equipment maintenance works and with 1 skilled operator who will oversee this process. This results in a 31.40% project cost savings, and 58.70% programme squeeze against the baseline.

Deployment scenario 2 assumes that the fully autonomous equipment will work for two 9.5-hour shifts in a in a 24-hour period to complete Project A. However, each of the 5 work elements will be paired with one skilled operator working as a computer machine controller available per shift. Machine controllers will be responsible for overseeing the autonomous operation of the equipment should a human intervention be required. Project A will thus require 5 computer machine controllers working in a control room per 9.5-hour shift. This accounts for 19 hours for the double shift and 10 machine controllers for deployment scenario 2 over a 24-hour period as against the original 38 machine operators used on Project A. This translates into 23.76% project cost saving and a 50% programme squeeze when compared against the Project A baseline. Given that in the real-world, issues like noise rules or the safety of night staff might stop machines from working 23 or even 19 hours a day, two additional deployment scenarios were analysed.

Deployment scenario 3 and 4 assume a 9.5-hour shift, which is the same working time in the baseline scenario. However, deployment scenario 3 only requires 1 skilled operator who will oversee the shift whilst deployment scenario 4 will require one skilled operator working as a computer machine controller for the 9.5-hour shift. This will require 5 computer machine controllers who will be paired with each of the 5 work elements for every shift. Both deployment scenarios do not translate into any programme squeeze but scenarios 3 and 4 will result in a project cost saving of 31.4% and 28.01 respectively.

4.2 Interview results

The interview results revealed 4 themes, which were, current knowledge, attitude and perception towards full automation, barriers and benefits of full automation.

4.2.1 Current knowledge, attitude and perception

Unwittingly, interviewees initially mistook ‘fully autonomous’ for current levels of automation involving widespread GPS systems and sensors for automated machine control and guidance [1]. According to interviewees, this now seems to ‘just be a part’ of everyday construction. They acknowledged fully autonomous equipment for earthworks could be a future reality but expressed doubt that unmanned equipment could take over on their earthwork projects anytime soon. There was a consensus that given the length of time for which semi-automation using GPS systems and sensors had become the norm, initial fears about the disruption that can be caused by automation was now diluted. Site managers had now widely accepted the current level of automation and machine assisted guidance using GPS systems as beneficial and are positive about its utilisation. However, they often could not envisage past the current GPS technology in terms of how artificial intelligence is fast pushing the boundaries into full automation. Suggestions were offered for full automation to focus more on material distribution on site (for example replacing forklift or telehandler drivers) rather than the earthworks as part of a gradual process towards full automation to minimise the potential disruption of replacing all operators with machines.

4.2.2 Barriers to full automation

Interviewees expressed reservations about the extensive upfront capital and time investment needed to achieve full automation and if the benefits will be worth the effort which is not surprising given the historically lower capital intensity and investment in construction compared to other industries [15]. Scepticism about the benefits of such investment outweighing the social cost was raised. The views expressed were that replacing machine operators was detrimental to the social value contributions of the industry. Strong sentiments were expressed that any abrupt switch to fully autonomous equipment will lead to socio-economic pressures arising from unemployment and redundancy payments. They amplified the social cost and morality of deploying fully autonomous equipment as a defence for retaining skilled machine operators. There is thus a need to pursue a careful balance between full autonomy for productivity and efficiency gains and sustaining the social value contributions of the construction industry, which according to Watts et al., [16] is predominantly measured through non-financial metrics.

Concerns were also raised about SME's being left behind due to financial constraints and the inability to get involved in research and development activities to test fully autonomous equipment. Views were that large companies will lead the way given the extensive upfront investment of capital and time needed. The culture of cynicism in construction towards acceptance of new, and disruptive technology also led to suggestions that an incremental introduction may provide a better route to implementation. Doubts were also raised about the reliability of AI systems that power fully autonomous equipment in terms of their reactiveness and adaptiveness to complex site conditions during earthworks as against the value of experienced machine operator. Views were that AI-systems could be inadequate at present to achieve a self-learning and intuitive adaptiveness for different earthwork conditions. An illustrative statement from one of the interviewees to this effect was that "Operators are always needed because they can recognise and react quickly to changing conditions, or to fast developing problems". The adaptiveness required for the equipment-to-equipment collaboration to execute the sub-activities for project A in Table 4-8 will even be more complicated to achieve without any human input. Despite these doubts in the technical feasibility, Shojaei and Burgess [17] found that the risk-averse culture in construction, which is an integral part of the socio-technical structure of the sector, can inhibit widespread adoption of digital technologies even when there is no technical challenge. This culture of cynicism towards the new and disruptive extends to the deployment of fully autonomous equipment given the above findings.

4.2.3 Benefits of full automation

Participants acknowledged some elements of increased productivity from the introduction of 'fully' autonomous equipment such as overcoming human error. The nature of human mental capacity means that complacency and mistakes can set in and removing the human element offered the possibility of eradicating the waste in time and cost from human error. The safety benefits of less injuries or fatalities and the opportunity to tackle challenges in recruiting experienced operators were also acknowledged. Profit from labour cost savings could be realised, though this was considered a one-sided benefit experienced by people 'at the top', with no one thinking about protecting the 'people at the bottom' in a difficult industry. These findings support the need for a human centred approach that prioritises human-autonomous machine collaboration for earthworks. This will balance the efficiency gains with the social value benefits that the sector provides through skills and employment opportunities. Whilst the technology continues to evolve at a fast pace towards full autonomous deployment, it is important to ensure ethical implementation as a tool for workers (enhancing human performance) rather than as a replacement of the workers (replacing human performance).

5. Conclusion

The analysis has revealed that the benefits of full automation can be significant i.e., potentially between 50% - 59% programme squeeze and 24% - 32% labour cost savings for this case study project across 4 deployment scenarios. Participants acknowledged some benefits of fully autonomous earthwork equipment such as reduced human error, enhanced safety, and the mitigation of skilled labour shortages though challenges were emphasised. These challenges include the high upfront investment, socio-economic concerns related to job displacement, cultural resistance and technical feasibility of equipment being able to intuitively react and adapt to the complex site conditions. Participants suggested incremental implementation to minimise the social cost to the industry. Findings imply that the deployment of fully automated equipment for earthworks remains promising but contentious, requiring a balanced approach that alleviates the social and ethical concerns. Deployment strategies that seek to augment rather than replace human roles will thus need to be prioritised to achieve productivity gains whilst preserving the social value benefits offered by the sector.

The study is not without limitations. First, only illustrative scenarios are analysed against a single case study project which cannot be generalised. The interviewed participants were also limited to those linked to the case study project which limits generalisability. The cost and time savings are based on assumptions that fully autonomous equipment will perform at the same output and reliability as those used in the case project, but this has not been tested in practice. Deployment of fully autonomous equipment for earthworks of the scale studied in this case will require multiple equipment working together autonomously, which is much more complex and has not been achieved in any of the current field trials. Thus, only a theoretical scenario analysis could be undertaken. Future research will be needed to analyse and compare the wider impact of deploying automated equipment across a range of earthwork activities using field studies as trials are scaled up. Future research could focus on developing a framework to guide the ethical integration of fully autonomous equipment for earthworks.

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