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Manufacturing in Space

Adaptive In-Orbit Servicing of Altered Satellite Components

Production Control in Space

Customized Organs from Space

“Entrepreneurial courage is the key ingredient”
A Conversation with Jan Wörner, Frankfurt
Institute for Advanced Studies (FIAS)

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Editorial

Space and Its Infinite Possibilities

Space has fascinated me for decades. In the past, science fiction television series were the main source of information about the infinite possibilities offered by space. I'm not referring to Hollywood blockbusters such as Star Wars but serious series based on scientific findings, foremost among them Star Trek: The Next Generation. In this series, space exploration always went hand in hand with scientific discovery. Some episodes even dealt with papers submitted at scientific conferences taking place on beautiful planets. Manufacturing sometimes featured in these series, mostly focused on the mining of rare materials but also on the construction and repair of spaceships outside the planetary atmosphere.

In the German and international research landscape, the topic received little attention following the euphoria of the moon landing in the 1970s. The construction and positioning of satellites took place practically outside the public's perception. One man has changed this dramatically in recent years: Elon Musk. He applied many principles of modern production and logistics to space technology for the first time at his company SpaceX, such as reuse at all stages of rocket production, autonomous landing on sea platforms, and the continuous scaling of both the number of rockets produced and the size of the rockets.

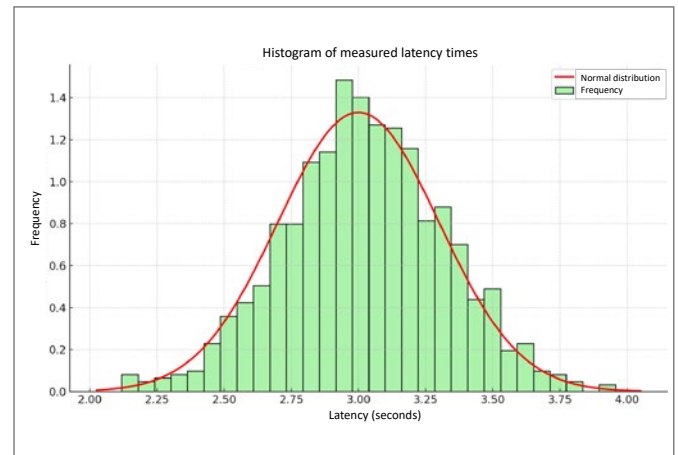
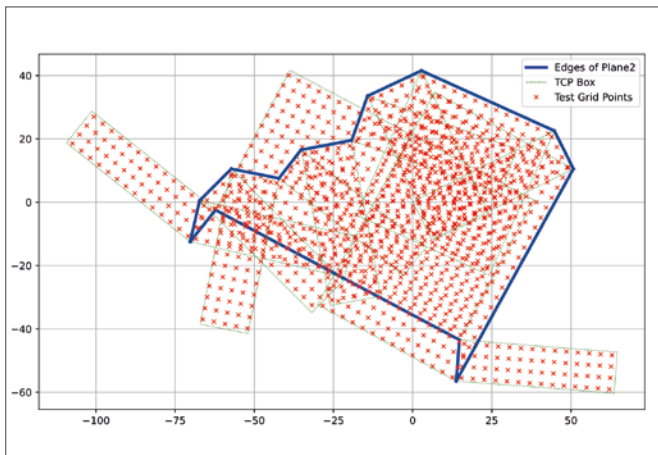
This has opened up a multitude of new perspectives. Germany has begun to recognize that space offers infinite possibilities. The first German rockets were launched and new launch sites were developed alongside the much too slow ESA. A ministry was even (partly) dedicated to space travel. In my opinion, the topic "manufacturing in space" reveals a plethora of opportunities, but also challenges. Some of these are discussed in this issue of Industry 4.0 Science. To quote Captain James T. Kirk: I can only urge research and industry to continue to boldly go where no one has gone before.

Prof. Norbert Gronau
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In-orbit servicing of satellites presents several challenges as the satellite hardware is exposed to external influences throughout its life cycle. This paper proposes an approach involving an adaptive grip position estimation in a CubeSat disassembly process.

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Production Control in Space

Production in space sounds like science fiction—but it could soon be reality. In the future, medicines, semiconductors, and even tissue will be produced in orbit. But how do you control complex systems many kilometers away? With mathematical precision and artificial intelligence.

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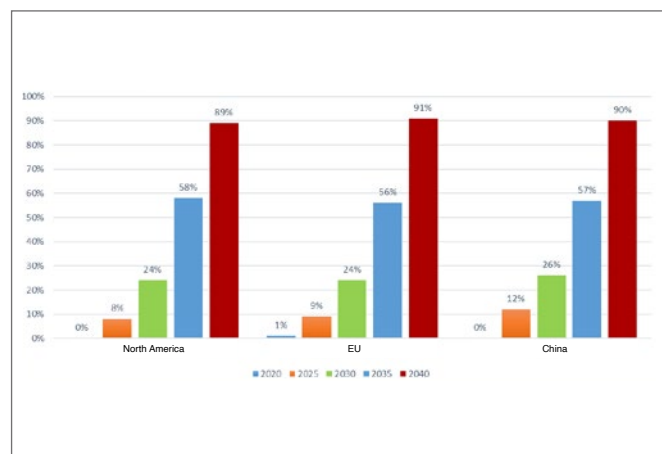
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	Interview				Summary							
	Duration (in min.)	Breadth	Depth	Conversation Atmosphere	Completeness	Relevance	Redundancy (number)	Input Fidelity	False Information (0 = not included, 1 = included)	Clarity (expert 1)	Clarity (expert 2)	Overall Clarity
Expert A, Topic: prompt engineering	10:26	3	4	4	4	4	4	4	1	3	3	3
Expert A, Topic: personalized chatbot	12:00	3	3		3	4	4	3	1	3	3	3
Expert A, Topic: requirements for a chatbot	8:27	2	4		3	4	3	2	1	4	3	3,5
Expert B, Topic: optical quality control	11:02	4	3	4	4	3	3	4	1	4	3	3,5
Expert B, Topic: circular economy, recycle system	13:30	3	3		2	3	0	4	0	3	3	3
Expert B, Topic: public funds	9:15	3	3		2	3	4	4	0	4	4	4
Expert C, Topic: manufacturing process "balancing"	8:23	4	4	4	3	4	2	4	1	4	3	3,5
Expert C, Topic: manufacturing process "shrinking"	6:27	4	4		3	4	1	4	1	4	4	4
Expert C, Topic: joining of car body panels	10:20	4	3		2	3	0	3	0	3	3	3
Average	9:58	3,33	3,44	4,00	2,89	3,56	2,33	3,56	0,67	3,56	3,22	3,39

Evaluation Scale (1-4): 1 = fully applies; 2 = rather applies; 3 = rather does not apply; 4 = does not apply at all



Potentials, Premises, Perspectives

Generative AI, including large language models (LLMs), is developing rapidly and being harnessed in more and more sectors. Against the backdrop of demographic change, the question arises as to whether LLMs can also support knowledge management in companies.

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Electric Trucks in Intermodal Terminal Pre- and Post-Carriage

Electric trucks (e-trucks) are considered a promising solution for more climate-friendly logistics. But how well can e-trucks actually be integrated into the operation of intermodal terminals? What challenges arise in terms of planning, charging infrastructure, and energy supply?

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HALL OF EXCELLENCE

Outstanding Reviewers Award

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With this award, we would like to recognize the top three contributing reviewers who have enriched our publication with their knowledgeable judgment. These reviewers have exceeded all expectations in their evaluations of the soundness, originality, and quality of "the texts submitted to our publication. The recipients of this award have helped raise the standard of our publication and the ideas presented by our authors.

The editorial team at GITO Media would like to acknowledge their outstanding contributions and express our hope for a continued cooperation in 2026.

Berlin, at December 2025
Marcel Rojahn, MS, Editor-in-Chief



Industry 4.0
SCIENCE

Turn uncertainty into opportunity.

AI predictions your teams can trust.



AI that works in business and is more than clever sounding

European companies have invested massively in AI in recent years, as if someone had shouted “all in” and without limits. Billions for smarter planning, better forecasts, less waste, more efficiency. Sounds like the future, smells like progress. But the disillusionment has already set in. Two-thirds of AI projects are stuck in the pilot phase not because the systems are bad. But they come up with inexplicable decisions.

This is not due to the technology as it is capable of far more than the teams believe. Maximilian Gismondi, CEO and founder of Backwell Tech, sums it up perfectly: “It’s the black box dilemma.” If an AI tells the production manager, “Change these parameters!” or “adjust this pricing,” the manager has two options and can either blindly follow or ignore the recommendation. And because no one can argue “the algorithm said so” in a million-euro decision, it usually comes down to option two: ignore it and carry on as usual.

To address this critical issue, the Berlin-based scale-up Backwell Tech is launching its Explainable Predictive AI (XAI) on the German market. The company is on a clear mission to come up with accurate and understandable AI. Only when teams can understand why a business recommendation is generated can it be implemented effectively—and thus deliver real economic benefits.

“AI-supported forecasts must be understandable and verifiable; otherwise, they are not economically viable,” says Maximilian Gismondi. “Transparency is essential for building trust in data-driven decisions.”

Backwell Tech is therefore introducing an AI platform that delivers targeted, precise predictions on key business metrics based on company data rather than something only comprehensible to insiders. When they make a recommendation based on forecasts, they also provide the story behind it, i.e., data, trends, signals, and market behavior. No mystical algorithmic fog from a black box, but rather comprehensible chains of cause and effect. This is exactly what managers need when they have to explain decisions to the board, authorities, customers, or simply their own team.

Backwell Tech’s systems demonstrate something that is often overlooked in many strategy decks: AI rarely fails because of its intelligence. It fails because people do not trust it. And without trust, there’s no implementation. If AI does not impact business, it will remain on the level of an expensive pilot project as has already occurred in many companies. Those who want AI to finally deliver need smarter models and a technology that can explain its recommendations.

Backwell Tech does precisely that: AI that does not require the blind faith of an oracle but that can be understood, tested, and defended. This is what distinguishes an expensive pilot project from a genuine competitive advantage; this is what transforms uncertainty into opportunity; this is what delivers trustworthy AI predictions for the team.



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THANK YOU

The editorial team would like to thank all the reviewers who contributed to the 2025 issues with their expert judgment.

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Adaptive In-Orbit Servicing of Altered Satellite Components

Maintaining satellites in orbit is difficult because the hardware is exposed to external influences throughout its life cycle. Collisions with space debris wear down components and alter their structure. In these cases, pre-planned disassembly processes often no longer work due to changes in surface geometry. A method for determining the best gripping position for automated robotic disassembly can help here.

Keywords

in-orbit servicing, artificial intelligence, small batch repair, robotics, pose estimation, CubeSat, space technology, satellites, disassembly

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Adaptive In-Orbit Servicing of Altered Satellite Components

Adaptive gripper placement on altered components for servicing in-orbit satellites

Justus Rein, Christian Plesker, Adrian Reuther, Hanyu Liu and Benjamin Schleich,
PLCM - Technical University of Darmstadt

In-orbit servicing of satellites presents several challenges as the satellite hardware is exposed to external influences throughout its life cycle. These factors wear down the components and cause changes to their physical structure. In such cases, the limits of simple dis- and reassembly steps may be reached, as the gripping surfaces are no longer present or suitable. This paper proposes an approach of an adaptive grip position estimation in a CubeSat disassembly process. The relevant components are identified using CAD models and a 3D camera. The gripping positions are determined based on the geometry of the gripper and the point cloud of the component.

Given the concept of “New Space” and the associated developments in commercialization and privatization, space travel is entering a new era. This latest era is characterized by new mega-constellations such as OneWeb, Starlink, Kuiper, and Guowang and which are leading to a significant increase in the number of satellites in orbit [1]. The increase in satellites is resulting in serious problems such as space debris. In its annual “Space Environment Report 2025” [2], the ESA put the increased number of objects tracked at almost 40,000. A particular problem arises with satellites that have spun out of control and cannot return to orbit. This situation is exacerbated by the lack of in-orbit servicing capabilities. New concepts such as the in-orbit factory [3] offer alternative solutions. In the long term, it seems sensible to minimize the costs incurred and resources used in the satellite sector by considering the possibility of direct maintenance or repairing defective satellites in orbit. This could lead to an extension of the active service life of individual satellites and a reduction in the need for new satellites. Instead of using complete satellites, significantly lighter spare parts as raw materials could be sent directly to an in-orbit factory, which does automated in-orbit servicing. This would be a sustainable way of reducing costs and space debris. However, it should be noted that in-orbit servicing presents several

challenges. External influences during rocket launch and the operational phase in orbit (collisions with asteroids, space debris, or other active satellites) can alter the physical structure of satellites. In some cases, existing (dis)assembly steps can no longer be carried out as planned

because the gripping surfaces are no longer available or the component inertia and/or dynamics have changed significantly. Thus, an adaptive method is needed to identify gripping surfaces on the components. This is essential to ensure automated maintenance of the satellites in changed conditions.

State of the art for in-orbit servicing

In-orbit servicing needs to be solved first to reduce both space debris and the high costs of launching satellites. The main objectives of in-orbit servicing can be divided into life extension/station keeping, refuelling, de/re-orbiting, salvage & recycling, relocation, robotic manipulation, in-orbit assembly and manufacturing [4].

As human involvement in orbit is extremely costly and teleoperation has its limitations, novel approaches are being developed to establish fully autonomous factories in orbit using AI, which can take over these tasks [5]. The core principle of the in-orbit factory concept involves the use of articulated arm robots, which allow for flexible operation. The factory itself is orchestrated autonomously by a digital process twin [3]. In addition to executing the individual process steps, the digital process twin provides all the relevant information from the necessary components, instructions, and 3D models to simulation and error detection via sensors such as cameras or force sensors. The primary benefit of such a facility is that components can be transported directly to the factory. Consequently, satellites themselves no longer require protection from launch and vibrating structures. This facilitates the development of lightweight structures, which are more sustainable and lower both weight and transport costs.



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Another obstacle is the heterogeneity of the satellites themselves. The commercialization of the aerospace industry, coupled with a lack of interoperability, has paved the way for a wide variety of satellite solutions and structures. A significant number of the steps involved in in-orbit servicing require components to be dismantled or replaced. Consequently, the assembly robot arm must be capable of flexible control.

A skill-based disassembly approach offers a flexible and hardware-agnostic method for performing these dismantling operations. A skill provides a robotic system with a high-level capability [6] and can be combined with other skills to achieve more complex tasks, such as an entire disassembly process [7]. One major advantage of the skill concept is that skills represent abstract, human-readable functionalities. Even in fully autonomous operation, engineers can monitor the robot's operational state at any time. Furthermore, skills are not necessarily bound to specific robotic functionalities. They can be applied to other machines, peripheral devices or even software modules within the same system, enabling a wide range of application scenarios. This abstraction facilitates the transfer of operational logic across heterogeneous hardware platforms. For the automated handling of deformed or damaged satellite components, skill-based task decomposition proves especially advantageous. A sequence of skills may be defined, starting with the acquisition of a point cloud of the target object, followed by a skill for grasp position estimation, and finally a skill for the actual grasp execution. Such modular sequences have been successfully demonstrated in existing research [8, 9] as an effective approach to object manipulation in uncertain or changing environments.

Vision-based robotic grasp detection systems require object localization, object pose estimation as well as grasp estimation, which can be included in the aforementioned robot skills [10]. Grasp estimations based on point clouds often use pose estimation to calculate the required values for the grasp end effector Tool Center Point (TCP). These estimations are suitable for various types of end effectors and part geometries and reach average success rates of around 80–100% depending on the part geometries [11–13]. Moreover, these algorithms currently lack the required accuracy for unmonitored in-orbit servicing in space. Grasping of unknown parts has been prototypically demonstrated but often has constraints due to simplified implementations and lacking accuracy [14].

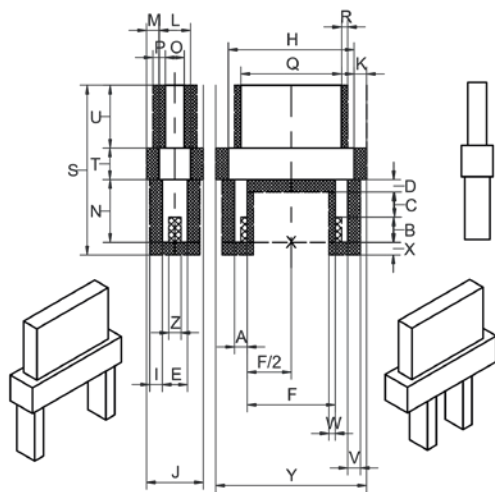
Preliminary research results indicate the benefits of an automated in-orbit factory equipped with articulated robotic arms for satellite servicing [5]. The decomposition of robotic tasks into discrete skills has emerged as a promising approach to enhancing the flexibility of automated operations [8, 9]. The development of estimation skills is contingent upon the geometry of the

object in question. This capability is often constrained by factors such as the geometry of the end effector [14]. The identified research gap stems from the absence of automated and adaptable mechanisms that enable robotic skills and tasks to be flexibly adjusted when repairing components with altered geometries.

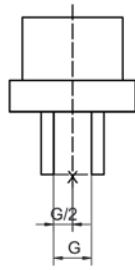
Adaptive gripper placement for in-orbit servicing of satellites

Building on the concepts of skill-based task modeling presented by Trautner et al. [8] and Parigi Polverini et al. [9], the proposed approach decomposes the disassembly task into modular skills, enabling the flexible adaptation of robot behaviors to altered component geometries. Furthermore, the vision-based grasp estimation principles outlined by Du et al. [10] are incorporated into the proposed methodology through the integration of point cloud-based object localization, pose estimation, and grasp point determination. The subsequent method is designed to facilitate automation of satellite disassembly within an in-orbit factory, employing articulated arm robots and parallel gripper end effectors. The process is built on existing 3D models of the CubeSat components in their original condition. Furthermore, a point cloud file of the space factory environment, in conjunction with an existing sequence of working steps as well as path and trajectory planning for the disassembly task are required. The proposed method is illustrated in **Figure 3** as a UML activity diagram and is independent of the technology used. For the sake of simplicity, it is assumed that all end effectors are symmetric and only parallel gripper end effectors are considered for the in-orbit use case where end effectors cannot be applied due to the missing air vacuum suction. For end effectors with unsymmetric geometry, calculations are based on the parameter values that produce the most unfavorable (worst-case) effects, ensuring the highest degree of safety in the approach. **Figure 1** depicts the parameters and **Figure 2** showcases their correlations. The values used for the parameters for the implementation are available in the GitHub repository [15].

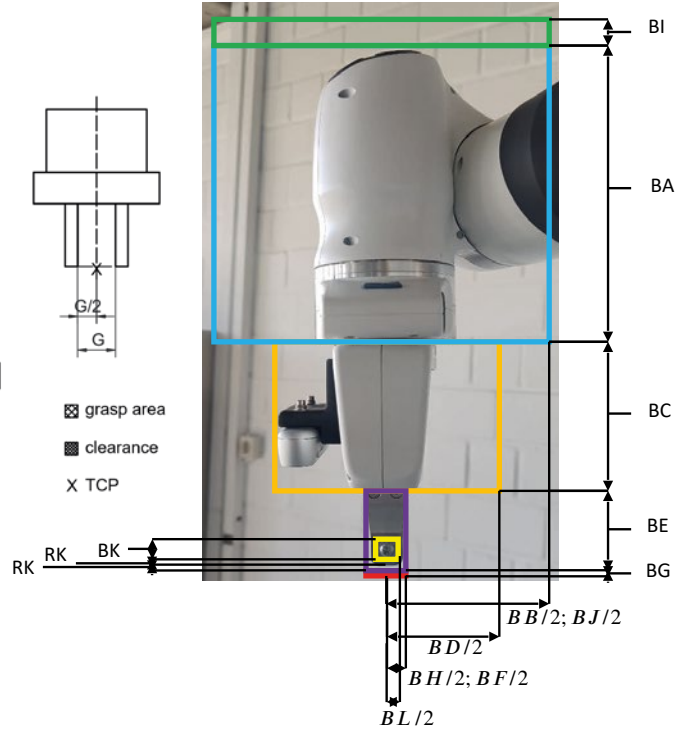
Initially, a defective CubeSat and its environs are captured from multiple angles employing 3D point clouds. To accomplish this, a 3D camera could be attached to a robot arm or multiple cameras could be used. These generated point clouds are subjected to a series of preprocessing steps, which include the removal of points outside the camera's range. Subsequently, the individual point clouds are unified into a single point cloud. The individual points of the background and the CubeSats are then sorted into individual clusters (**Fig. 4d**). The point cloud of the CubeSat is compared with a 3D model database to determine the CubeSat type (**Fig. 4e**). The individual components of the CubeSat assembly are then identified and positioned on



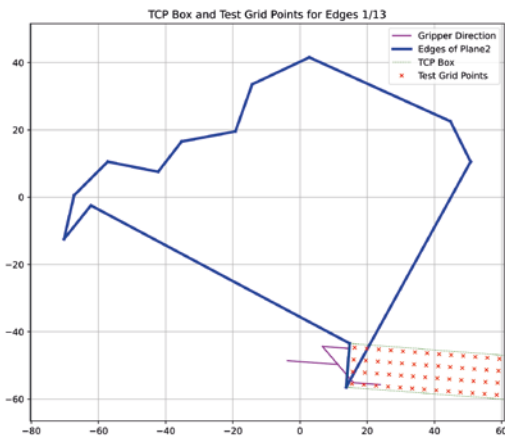
(a) gripper open



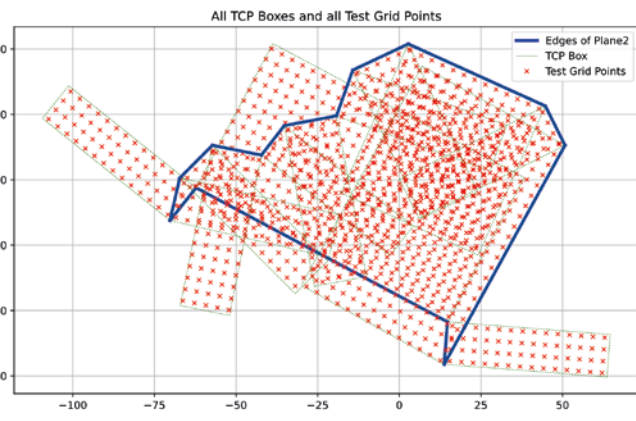
(b) gripper closed



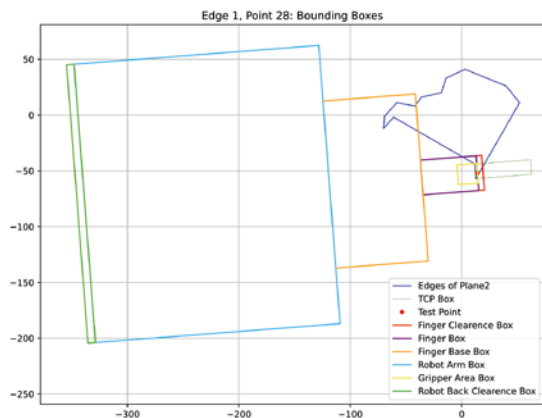
(c) rectangles robot placement



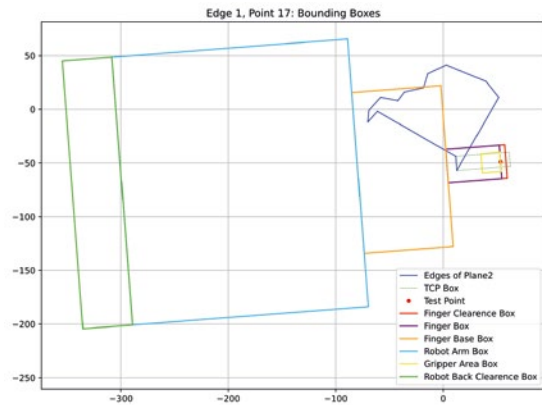
(d) TCP test grid for one edge for one plane pair



(e) all TCP test grids for one plane pair



(f) rectangles robot placement example 1



(g) rectangles robot placement example 2

Figure 1: Parameters for the gripper and robot.

Symbol	Geometric meaning	Value source	Symbol	Geometric meaning	Value source
BA	length blue rectangle 1	$RC+2\cdot RF+2\cdot RK$	CA	borders plane 5	$BP\leq CA\leq BQ$
BB	width blue rectangle 1	$RD+2\cdot RE+2\cdot RK$	CB	test grid width	edge length
BC	length orange rectangle 2	$U+T+D$	CC	test grid length	$B+C$
BD	width orange rectangle 2	$J+2\cdot RK$	CD	Plane distance 02	$BO+A+W+V+RK$
BE	length purple rectangle 3	N	CE	Border plane 3	$BO<CE<CD$
BF	width purple rectangle 3	$E+2\cdot(I+RK)$	AA	allowed angle between parallel planes	estimated
BG	length red rectangle 4	X	AB	minimum intersection area gripper	$AC\cdot B\cdot Z$
BH	width red rectangle 4	$E+2\cdot(I+RK)$	AC	Percentage of gripper area as minimum required overlapping area	estimated
BI	length green rectangle 5	$BM+X$	AD	intersection area gripper	intersection area of plane 1 and yellow box
BJ	width green rectangle 5	$RD+RF+2\cdot RK$	RA	width of last robot arm limb	robot value
BK	length yellow rectangle 6	$B-2\cdot RK$	RB	depth of last robot arm limb	robot value
BL	width yellow rectangle 6	$Z-2\cdot RK$	RC	length of last robot arm limb	robot value
BM	distance edge to tested point	length edge normal vector to tested point	RD	maximum diameter of last robot arm limb	$\max\{RA, RB\}$
BN	allowed distance of plane A and plane B	$BT\leq BN\leq BU$	RE	robot arm diameter clearance	estimated
BO	plane distance 01	BN^2+RK	RF	robot arm length clearance	estimated
BP	plane distance 03	Y^2+RK	RG	repeatability of robot arm	robot value
BQ	plane distance 04	$RD^2+RF+RK$	RH	inaccuracies Intel RealSense D415	estimated
BT	min. distance parallel planes	$G-2\cdot RK$	RI	inaccuracies edge detection	estimated
BU	max. distance parallel planes	$F-2\cdot(W+RK)$	RJ	inaccuracies of scene capturing (camera attached to Franka)	robot value
BV	test grid point distance width	$Z/5$	RK	sum of inaccuracies	$RG+RH+RI+RJ$
BW	test grid point distance length	$B/5$	IV₁	impact value 1	determined
BX	borders plane 1	overlapping points from plane A and B	IV₂	impact value 2	determined
BY	borders plane 2	$\leq BO$	SV₁	success value 1 based on distance to surface center	$SV_1=1$ for TCP in center of mass; $SV_1=0$ for furthest point in point cloud; linear correlation
BZ	borders plane 4	$CD\leq BZ\leq BP$	SV₂	success value 2 based on size of surface grasped	$(AD-AB)/(B\cdot Z-AB)$
			GSS	Grasp Suitability Score	$GSS=\sum_i SV_i\cdot V_i$

Figure 2: List with parameter calculations and correlations.

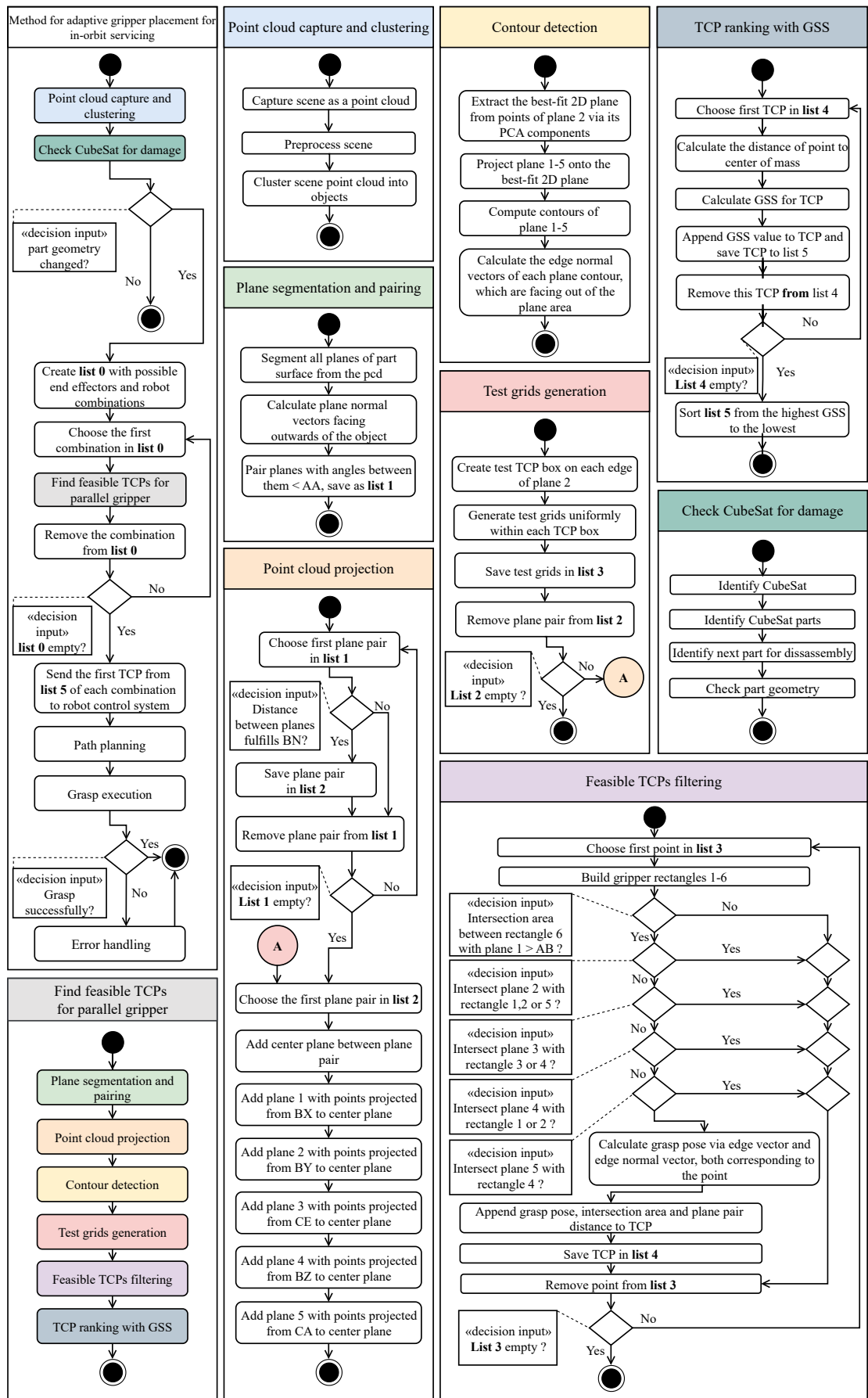


Figure 3: Method for adaptive gripper placement for in-orbit servicing.

the point cloud (**Fig. 4c**). The next component of the CubeSat to be disassembled is selected from the sequence planning and is compared to the point cloud to determine whether there has been a significant change in its geometry (**Fig. 4f**). Once the geometry changes—for instance, due to a collision with space debris—a new gripping position needs to be determined.

Subsequently, combinations of available robots and end effectors are created that use their parameters for further calculations. All available combinations will be used for the Grasp position estimations. Initially, all points of a part are grouped into clusters according to their affiliation to a planar surface geometry (**Fig. 4g**). The point groups are then assigned to pairs with other planar surfaces that are oriented parallel (**Fig. 4h**). The angle between both pairs needs to be smaller than α , and their normal vectors must face away from each other. If the planes also meet the BN requirement, they can be used as gripping surfaces. Furthermore, the gripping positions are also referred to as tool center points (TCPs). The points in surface A and B will be projected to plane 1 (**Fig. 4k**), which is in the symmetric center of plane A and B and contains the intersection areas of both surface points projected on the plane.

In the absence of intersection, the creation of a center surface and of the planes 2 to 5 is impeded. Subsequently, an additional plane “plane 2” (**Fig. 4l**) is generated, encompassing all points with a distance in BY in both positive and negative directions from the center plane. A third plane, “plane 3” (**Fig. 4m**), contains all points with a distance in CE. Plane 4 (**Fig. 4n**) contains all points with a distance in BZ and plane 5 (**Fig. 4o**) all points in a distance in CA. To facilitate the subsequent calculations, edge detection is employed to generate one or more areas per plane from the individual points for all four surfaces. All five planes lie on plane 1 with their plane’s normal vectors’ direction aligned (**Fig. 4j**). The determination of potential TCPs is predicated on the use of plane 2. The vector for each edge of the area pointing out of the area is identified by checking whether an infinitely long normal vector in the plane of the area intersects an even or odd number of edges (even = outward direction; odd = inward direction). The generation of a rectangle is initiated from each edge in the negative vector direction (**Fig. 1d** and **1e**). The width of the rectangle, designated as CB, is equivalent to the edge length, while its position is determined by the edge’s location. The length of the rectangle is CC.

Then, a test grid of potential TCPs is positioned within this rectangle, with a point spacing configuration in width BV and depth BW. This ensures that the entirety of the rectangle is filled symmetrically from the central point. The X, Y, and Z positions of the TCPs are determined by the position of the point in Cartesian space, and the rotation is defined by the direction of the negative normal

vector of the edge and the parallelism of the gripping surfaces to the symmetry plane. For each potential TCP, a combination of rectangles is placed to represent the individual components of the gripper and robot (**Fig. 1f** and **1g**). These are subjected to a collision check with planes 1 to 5. All remaining points are suitable TCPs.

A rank function (1), referred to below as the Grasp Suitability Score (GSS), is used to determine the optimal gripping point from all possible gripping points in accordance with [14].

$$GSS = \sum_i SV_i \cdot IV_i \quad (1)$$

This is achieved by weighing the Success Values (SV) with a corresponding Impact Values (IV) where SV_1 is correlated to the distance from the TCP to the object’s center of gravity and SV_2 is correlated to the size of the overlap area between the gripper finger and the object surface. Each point is assigned a GSS from 0 to 1, with a higher value indicating a better suitability of the gripping point (**Fig. 5**). The TCP with the highest GSS value is forwarded to the robot controller and replaces the original gripping position. All TCPs of the disassembly skill are adjusted by the offset to the original gripping point. An additional collision check is required to prevent collisions during movement in the skill, since only the gripping position of the end effector is considered during the method. Subsequently, the component gripping procedure is executed.

Evaluation and discussion of the adaptive gripper placement

To evaluate the adaptive gripper placement method, a simplified CubeSat assembly is employed. The evaluation is conducted by a Franka Research 3 robot arm with a Franka parallel gripper. **Figure 4a** depicts the unharmed CubeSat and **Figure 4b** the damaged one used for the evaluation. The CubeSat was captured with an Artec Eva 3D scanner. **Figure 4c** to **Figure 4o** depict the images created by the implementation which proves the functionality of the developed method for the adaptive gripper placement. A half-disassembled CubeSat is used because it better showcases the collision checks in the process of the grasp TCP estimation and the used end effector cannot grasp a closed CubeSat due to the maximum gripper distance of 80mm compared to a CubeSat with a size of roughly $100 \times 100 \times 100 \text{ mm}^3$. All possible TCPs are shown with a heatmap of their GSS values green=1 and red=0 in **Figure 5**. The software’s total runtime for different use cases was roughly between 0.5

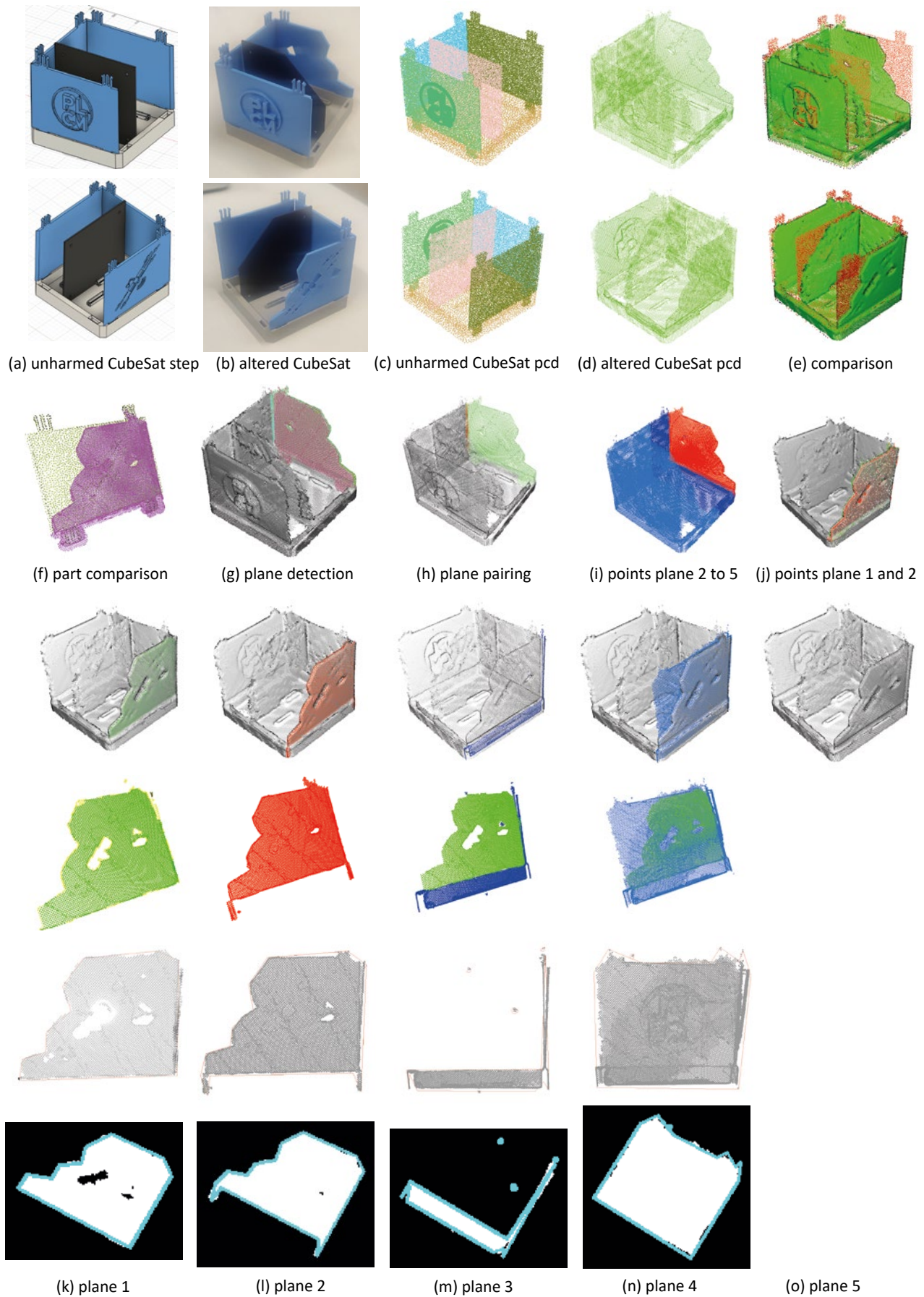


Figure 4: *Implementing the method.*

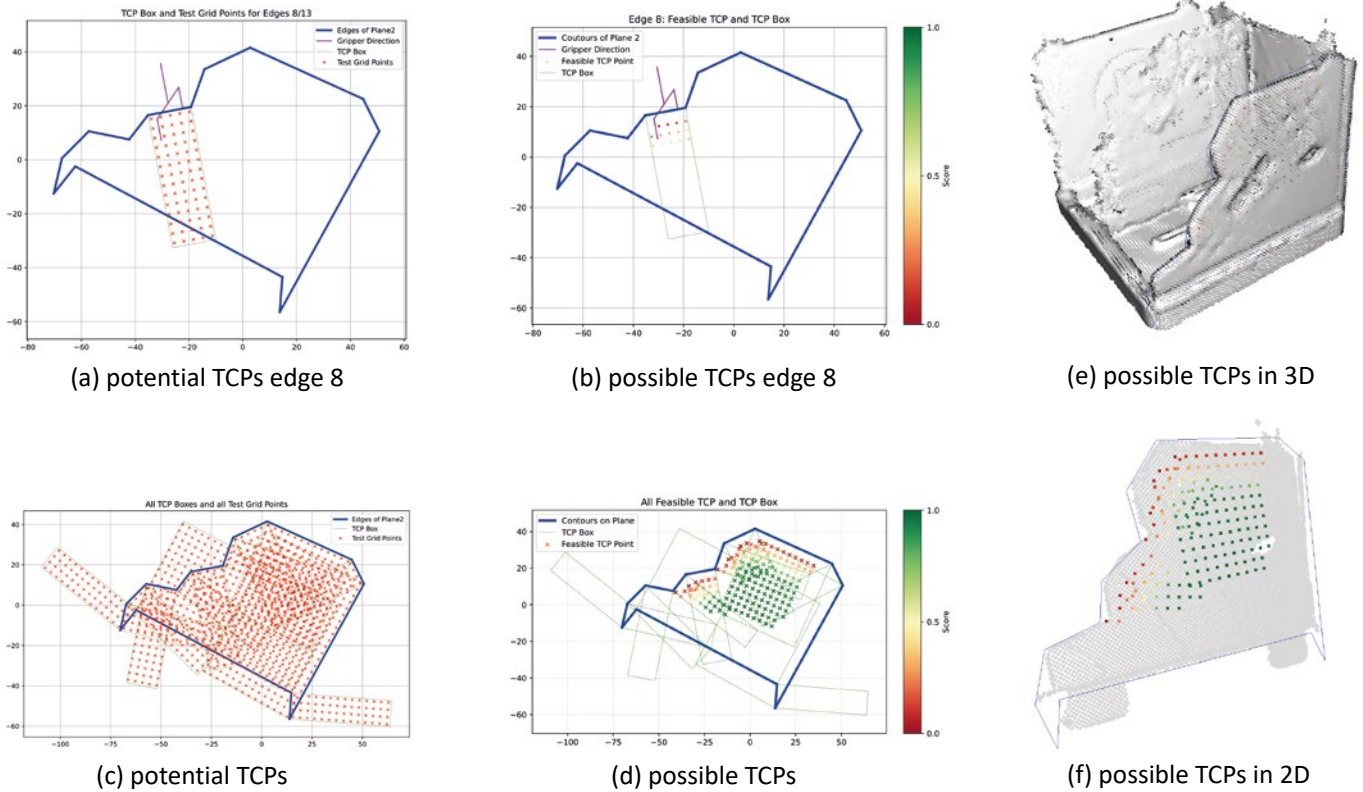


Figure 5: Results of the method.

and 5 minutes depending on the part complexity and point cloud density. However, there has been no effort to optimize the code's runtime, and this time is reasonable considering the number of satellites currently in space that need in-orbit servicing. The code written for the implementation, the 3D files and results are available at GitHub [15].

The current limitations of the implementation are that only planar surfaces for grasp estimation are used, which is no problem because the grasping of non-planar surfaces could lead to insecure gripping. That poses a high risk in an in-orbit factory due to unpredictable movements and damage from insecurely grasped and oriented parts in an end effector which could be released during a robot movement or could collide with the environment. The current method is only applicable for parallel gripper end effectors which can be assumed to the parameters of the end effector geometry in **Figure 1**. That concludes most of the industry relevant end effector types excluding vacuum suction cup end effectors which are not viable for an airless in-orbit factory. Due to the size and orientation of the test grids, not all possible grasping positions will be tested. This means that the optimal position may not be found, but that is not a problem because grasping requires only one viable position with a high enough chance of success. The approach presented here is the first step in overcoming the problem of components deviating during

the servicing of an in-orbit factory. As previously mentioned, this approach must now be expanded to include additional end effector types to enable flexibility and support more complex operations, such as screwing. Furthermore, the next step should be to investigate the use and data exchange with digital twins of the products. These could be an ideal basis for providing 3D models. Additionally, the virtual representation of the physical condition via the digital twin could support the process by providing further information, for example, in the event of already known damaged parts.

Summary and outlook for adaptive gripper placement for in-orbit servicing

Due to the increasing number of in-orbit satellites and their inevitable end of life, a method for in-orbit satellite servicing was presented. The proposed method can achieve adaptive gripper placement of altered components for in-orbit servicing, and it moreover archives a grasp TCP estimation for unknown parts. Both parts of the method can be used separately from each other in a modularized system. The grasp position estimation could be changed to an already proven grasp estimation algorithm, or the developed method could be advanced to consider more complex end effector geometries. The method uses rule-

based grasp estimation and Grasp Suitability Score calculations which are suitable for use in an in-orbit servicing factory. The only black box systems are machine learning-based edge detections and point cloud postprocessing, which use established algorithms but are prone to error. The method is independent of the technologies used and can be fully automated, requiring no human interaction during the repair process. In future steps, a sequence, path and trajectory planning for the in-orbit servicing as well as a digital process twin could be included in the method to achieve a fully automated flexible in-orbit servicing of CubeSats. The RISE mission, presented by the European Space Agency, exemplifies the potential applications and significance of this approach, as it is now launching a satellite equipped with robotic arms for in-orbit servicing [16].

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Bibliography

- [1] De Gaudenzi, R.: Satellite networks: Past Present and Future Challenges - Part 2: Broadband Systems. In: IEEE Aerosp. Electron. Syst. Mag. (2025), pp. 1–9. DOI: 10.1109/MAES.2025.3565491.
- [2] European Space Agency: ESA'S ANNUAL SPACE ENVIRONMENT REPORT. URL: https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf, accessed: 11.08.2025.
- [3] Leutert, F. et al.: AI-enabled Cyber-Physical In-Orbit Factory - AI approaches based on digital twin technology for robotic small satellite production. In: Acta Astronautica 217 (2024), pp. 1–17. DOI: 10.1016/j.actaastro.2024.01.019.
- [4] Opromolla, R. et al.: Future in-orbit servicing operations in the space traffic management context. In: Acta Astronautica 220 (2024), pp. 469–477. DOI: 10.1016/j.actaastro.2024.05.007.
- [5] Mühlbauer, M. et al.: AI-based Robust and Failure-Tolerant Processes for In-Orbit Manufacturing of Modular Small Satellites. 2024. URL: <https://mediatum.ub.tum.de/node?id=1755632>
- [6] Steinmetz, F. J.: Intuitive robot programming for novice and expert user. In: RWTH Aachen University (2022). DOI: 10.18154/RWTH-2022-08236.
- [7] George, P.; Cheng, C.-T. et al.: Task Complexity and the Skills Dilemma in the Programming and Control of Collaborative Robots for Manufacturing. In: Applied Sciences 13 (2023) 7, p. 4635. DOI: 10.3390/app13074635.
- [8] Trautner, T.; Ayatollahi, I. et al.: Behavioral modeling of manufacturing skills in OPC UA for automated execution by an independent cell controller. In: Procedia CIRP 99 (2021), pp. 633–638. DOI: 10.1016/j.procir.2021.03.085.
- [9] Parigi Polverini, M.; Zanchettin, A. M.; Rocco, P.: A constraint-based programming approach for robotic assembly skills implementation. In: Robotics and Computer-Integrated Manufacturing 59 (2019), pp. 69–81. DOI: 10.1016/j.rcim.2019.03.005.
- [10] Du, G.; Wang, K. et al.: Vision-based robotic grasping from object localization, object pose estimation to grasp estimation for parallel grippers: a review. In: Artif Intell Rev 54 (2021) 3, pp. 1677–1734. DOI: 10.1007/s10462-020-09888-5.
- [11] Ma, H.; Wang, G. et al.: Robotic grasping method with 6D pose estimation and point cloud fusion. In: Int J Adv Manuf Technol 134 (2024) 11–12, pp. 5603–5613. DOI: 10.1007/s00170-024-14372-3.
- [12] Bekiroglu, Y. et al.: Benchmarking Protocol for Grasp Planning Algorithms. In: IEEE Robot. Autom. Lett. 5 (2020) 2, pp. 315–322. DOI: 10.1109/LRA.2019.2956411.
- [13] Zapata-Impata, B. S.; Gil, P. et al.: Fast geometry-based computation of grasping points on three-dimensional point clouds. In: International Journal of Advanced Robotic Systems 16 (2019) 1. DOI: 10.1177/1729881419831846.
- [14] Rein, J.; Voges, J.; Reuther, A.; Schleich, B.: Method for determining the most suitable grasp tcp for robot part handling. In: Srihari, K.; Khasawneh, M. T.; Yoon, S.; Won, D. (eds): Flexible Automation and Intelligent Manufacturing: The Future of Automation and Manufacturing: Intelligence, Agility, and Sustainability, Lecture Notes in Mechanical Engineering. Cham 2026, pp. 347–354. DOI: 10.1007/978-3-032-07675-5_33.
- [15] Rein, J.: Adaptive-in-Orbit-Servicing-of-Altered-Satellite-Components. GitHub. 2025. URL: <https://github.com/JustusRein/Adaptive-In-Orbit-Servicing-of-Altered-Satellite-Components>. DOI: 10.5281/zenodo.16947439.
- [16] European Space Agency, in-orbit servicing mission RISE. [Online]. URL: https://www.esa.int/Space_Safety/ESA_to_build_first_in-orbit_servicing_mission_with_D-Orbit, accessed: 03.11.2025.

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Production Control in Space

Production in space, for example of semiconductors, offers many advantages for companies. At the same time, high transport costs mean that careful consideration must be given to which production materials are transported into space. The use of Kalman filters enables real-time control from Earth, making space production a cost-effective option. Machine learning means that this approach can also be applied to very complex production systems.

Keywords

production, machine learning, optimization, real-time control, industry in orbit



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Production Control in Space

An AI-supported approach for industry in orbit

Lara Jovic and Dominik Augenstein, Karlsruhe University of Applied Sciences

Production in space, of semiconductors for example, offers many advantages for companies. At the same time, high transport costs mean that careful consideration must be given to the production materials being transported. The use of Kalman filters enables (real-time) control from Earth, making space production a cost-efficient option. Machine learning could make it a viable approach even for highly complex production systems.

In an increasingly competitive environment, companies must explore new production methods. The main driver here is cost, which is fueling the current digital transformation but also leading companies to relocate their production to more economically favorable areas. In the near future, some experts foresee the first production facilities in space, or more precisely, in orbit. In just a few years, goods such as medicines, semiconductor crystals, and organoids (organ-like pieces of tissue) could be manufactured in this way [1].

The first in-orbit production is likely to take place in three to five years, as research into the required space capsules advances swiftly and innovators such as Elon Musk and Jeff Bezos manufacture powerful rockets [2]. The company Starship, for example, aims to manufacture completely reusable rockets with a capacity of several hundred tons, which will significantly reduce the cost of space travel. By way of comparison, sending one kilogram into orbit costs around \$2,700 with the current Space X Falcon 9. Starship aims to bring this down to less than \$500. Flying to the ISS or the moon costs \$20,000-40,000 and \$1 million per kilogram, respectively [3].

Every gram of weight sent into space must be carefully considered, for obvious economic (and ecological) reasons. This presents a dilemma: you want to establish production in space that meets standards on Earth. However, the costs of transporting the necessary systems, robots, peripherals, etc. will remain very high in the coming years, which could mitigate any advantages. One potential cost lever is to forego local, intelligent edge systems such as IoT edge devices or NVIDIA Jetson platforms and instead turn to centralized control from Earth. At the very latest when using artificial intelligence (AI), the systems will have to be controlled from Earth, as high costs would otherwise be incurred for the provision of the necessary computing power in space.

Control from Earth will thus be virtually unavoidable in coming years. However, this has the disadvantage that latency hinders the real-time capability of robots and

systems. If production is not located in orbit but on the Moon (or Mars), for example, this latency is significantly higher. This means, for example, that transport systems or robots controlled from Earth can only react to their

environment with a delay. The news of an obstacle ahead and the subsequent reaction take several seconds, which may be too late in some circumstances. In such cases, one can no longer speak of real-time capability.

Mathematical estimation methods, such as those used in radar technology to determine an aircraft's exact position and flight path, can help [4]. These methods can also be used to control a device in space in near real time and with greater accuracy, depending on the degrees of freedom that a system has (e.g., if it moves freely or along a predetermined route).

A model for (real-time) control of systems in space

To understand how mathematical functions help enable real-time control, let's use a simple example: You are driving your car into a tunnel and the GPS signal is lost. You want to take the next exit in the tunnel. How does the navigation device know where you are? It uses data from the vehicle sensors and the last known position to determine (approximately) where you are. In principle, it could calculate your location at any time based on your speed and last position. But this only works in a perfect world, because sensors are subject to measurement inaccuracies, interference occurs during data transmission to the microcontroller, or deviations occur in other places. This leads to inaccuracy in what is actually a simple piece of information: "speed".

In this simple model, one could now use so-called estimated values to eliminate disturbances and associated "distortions". This works quite well in this one-dimensional case [5][6], but a driverless transport system moving freely in space, for example, is already a multidimensional case not accurately captured with simple estimated values.

The same applies to our latency time. Although factors such as distance and weather conditions make it fairly

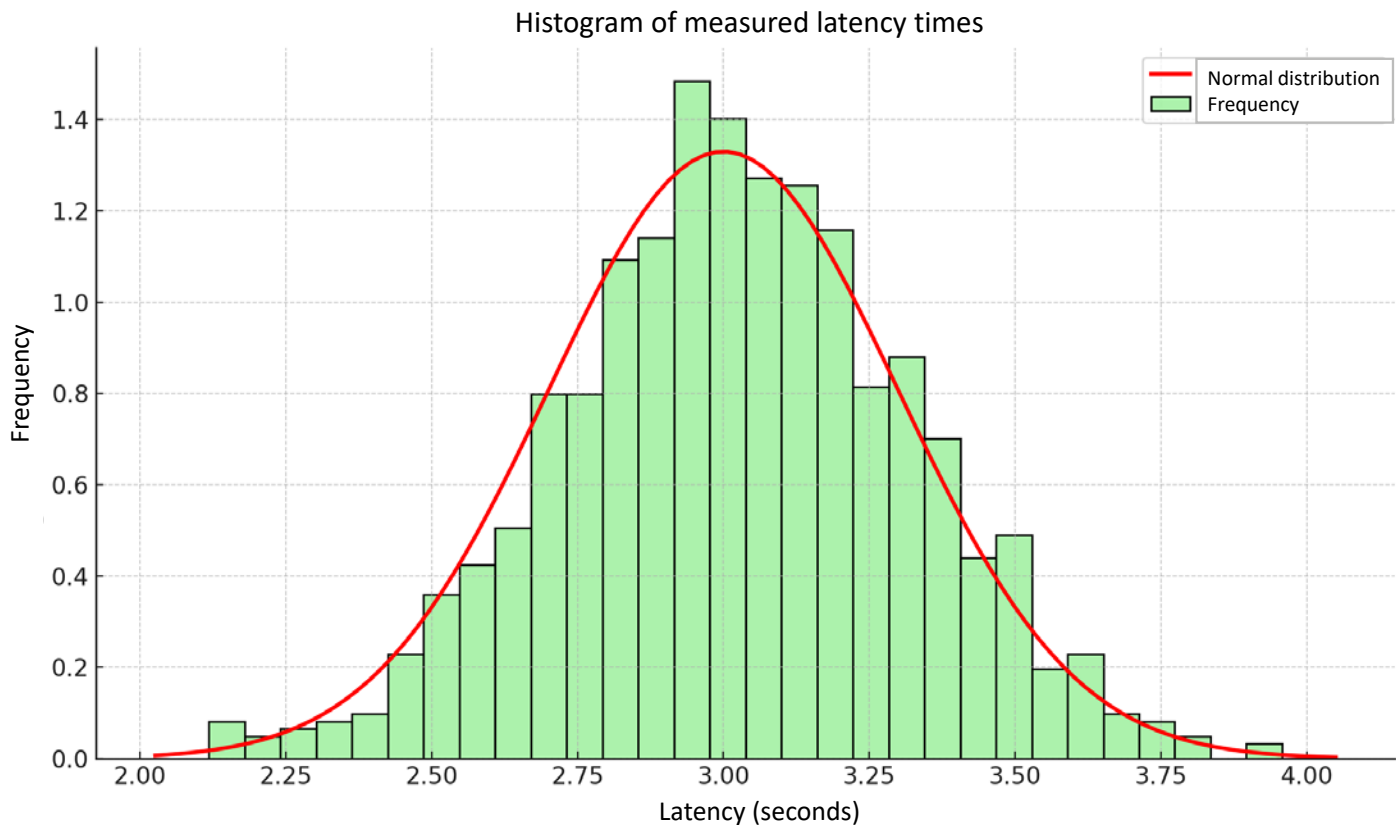


Figure 1: Histogram with sample data on latency.

constant, it is subject to a certain degree of inaccuracy. The following histogram illustrates this with an example: Although the maximum expected latency time is around three seconds, deviations in the millisecond range do occur. These deviations are called variance or “noise”. It is striking that the deviations are approximately normally distributed. This allows specific mathematical methods to analyze and correct the measured values.

In order to perform reliable calculations despite variance or noise, the “strength” of the noise must first be determined. This is determined individually for each sensor and taken into account in the calculations accordingly. The mean value is used—the expected value, e.g., the speed—as well as the variance of the normal distribution, which indicates how certain or uncertain the estimate is. As a general rule, the smaller the variance, the greater the confidence in the measured value. A sensor with absolute precision would theoretically have a variance of 0—a state that never occurs in reality [7].

In our navigation device example, we assume that the GPS signal has been lost and that the navigation device is unsure of its current location. Accordingly, the variance or uncertainty about the exact position is very high. In order to estimate a position nonetheless, other available data would be used, e.g., the measured speed. However,

the speed sensor also has a certain variance and is therefore also subject to uncertainty. Combining the uncertainties of the navigation device and the speed sensor yields a better result, allowing the navigation device to determine a more accurate current position. The navigation device knows “approximately” where you are and the sensor knows “approximately” how fast you are traveling, which allows for a relatively accurate statement in combination (this can be observed in everyday life: position determination in a tunnel is usually still very precise).

This approach was described by R. Kalman as early as 1960 and helped with the first moon landing [8]. Using the so-called Kalman filter, all you do is calculate a future position from the current position and check it (e.g., by taking measurements). These calculations and checks allow us to find the appropriate parameters to compensate for the “noise”, i.e., the variance. If the predicted values are close to the values measured afterwards, then the Kalman parameters are very accurate. In our example: If the car exits the tunnel at exactly the right moment (and has a GPS signal again, which enables location determination), then the estimation parameters are very well chosen. Otherwise, the parameters would be adjusted.

In our example, we are moving in a one-dimensional (maximum two-dimensional) direction; the example has



Figure 2: Example of position estimation and GPS calibration.

a low level of complexity. However, this forms the basis for the real-time control of significantly more complex production facilities in space. The position determination of a transport system on a planet depends not only on the respective distance, but also on the respective rotation, which is also subject to fluctuation. This gives us a complex system with several uncertainties, but we can easily reduce or even completely eliminate these by applying the mathematical model.

Development environments such as MATLAB include these Kalman functions, which makes creating and implementing such a mathematical model very easy [9]. Systems for controlling these devices in space could therefore be expanded by mathematical functions at low cost and with little effort.

That said, such systems are becoming increasingly complex and navigation and control are expected to become more autonomous with time. AI approaches can help: machine learning can assist in determining parameter values, for example, or a digital twin of production in space can be

created. AI can also be helpful in the case of fault-prone signal processing [10] or in dealing with parameters for target positions within an image plane in order to predict them. In the latter case, the position of the target is recorded in each iteration to predict the positions one step ahead [11]. This can also improve the position determination of driverless transport systems (in space). In principle, Kalman filters and their use in space production can themselves also be improved by AI.

Machine learning to improve Kalman filters in complex systems

As already described, the increasing trend toward machine learning algorithms not only creates new possibilities for AI-supported position determination but also makes Kalman filters and associated parameters more accurately predictable. The comparison of “estimated” and “measured” data in the application of Kalman filters represents a (historical) database, which can be used to train

corresponding AI algorithms. These can then reveal hidden patterns in the relationship between the estimated and measured data.

This does not work as accurately during dynamic scenarios brought about by system control or the routing of transport systems by AI. The parameters of the Kalman filters estimated by AI algorithms can quickly become outdated, as they are based on “past” data. However, an additional learning model can overcome this challenge by modifying the parameters according to the new conditions, even if these are caused by AI and are therefore sometimes difficult to predict [12].

This more advanced model consists of a prediction module and a learning module. The prediction module receives the measured and estimated values, such as the location and speed of a transport system in space. The module then determines the parameters of the Kalman filter and the exact location [13]. The learning module uses the same parameters as the prediction module, supplemented by additional influencing factors. Based on historical data and the associated parameters, the learning module calculates so-called “tuning” parameters that help the prediction module determine the optimal Kalman parameters. The combination of both modules enables precise determination of the status data and real-time control even given longer latency times.

The rapid progress in the field of deep learning algorithms and related technologies also has a positive effect on our approach. The targeted use of modern methods such as deep belief networks (DBNs), a hierarchically structured form of neural networks that recognize complex patterns

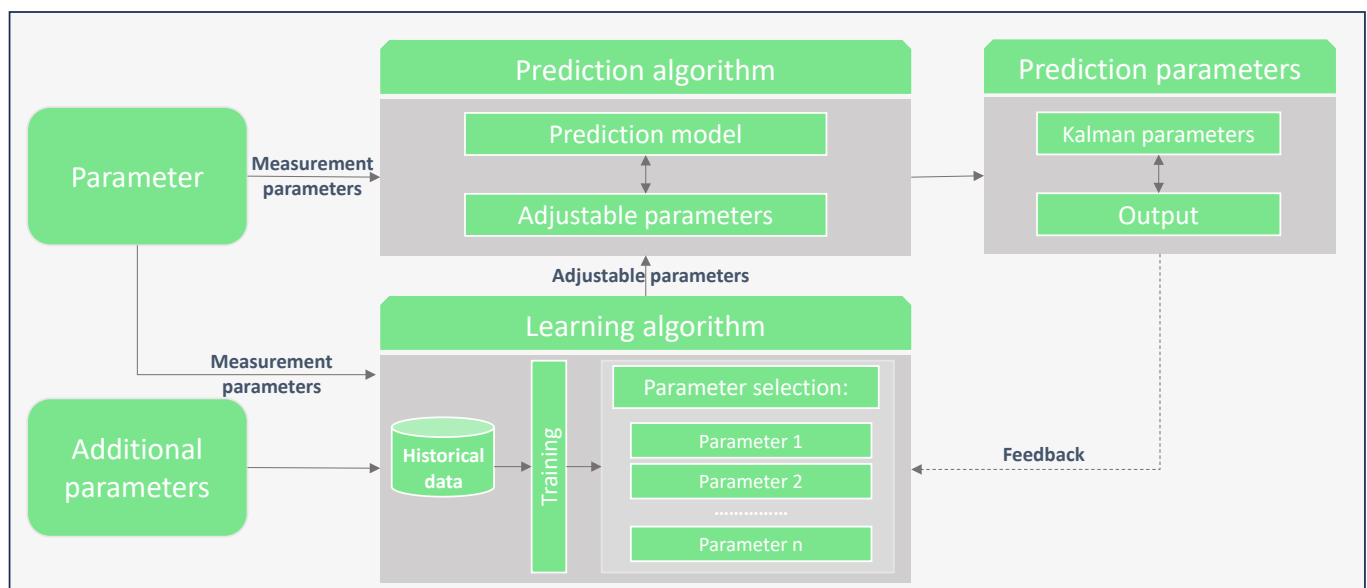
in data [14], or deep extreme learning machines (ELMs), which enable particularly fast learning processes through randomly initialized hidden layers, can significantly improve prediction accuracy [15].

Classic machine learning methods such as classification and regression trees (CARTs) can also be used [16]. These structured decision-making processes are represented in the form of tree diagrams, making them suitable for both classification and regression tasks. Support vector machines (SVMs), which are designed to find optimal separation lines (or hyperplanes) between different data classes, also make an important contribution to precise modeling [17].

All these methods are integrated into the learning module and trained using historical data. The aim is to derive so-called tuning parameters, which in turn increase the accuracy of the Kalman parameters used in the prediction module. In this way, the overall system can respond more robustly and reliably to dynamic changes in the input data.

In summary, the presented system architecture, consisting of a learning and a prediction module, represents a more precise approach for estimating variables using Kalman filters. By integrating modern machine learning methods into the learning module, adaptive tuning parameters can be generated based on historical data, enabling continuous optimization, even when using AI, e.g., for system control. This allows for increased accuracy, even in highly dynamic application scenarios such as those that can arise from the aforementioned AI-based control or system routing.

Figure 3: Overview of the learning and prediction algorithm for parameter estimation.



The promise of production in space

Production in space already appears very promising in near-Earth spheres. At the same time, the transport of the necessary production equipment still involves enormous costs. These can be reduced by controlling production from Earth, but latency and other uncertainties hinder real-time control at such great distances, which can lead to accidents.

In very simple cases, there are mathematical models that can provide accurate predictions. However, since production in space is complex, with many disturbances and uncertainties, and since the use of AI will make these models even more complicated in the future, the use of statistical methods such as the Kalman filter is essential. In these complex situations, machine learning algorithms can help to accurately determine the necessary parameters. Using a learning prediction model, these can be determined very accurately and even optimized during the learning process.

Although machine learning and necessary peripherals do incur additional costs, these are falling steadily and more and more training data sets are becoming available, so that this approach will also prevail in terms of cost in the long term. Compared to (falling) transport costs, they represent the significantly more cost-efficient solution in the coming years and are a central component of production in space.

Bibliography

- [1] Weinzierl, M.; Rosseau, B.: Space to Grow: Unlocking the Final Economic Frontier. USA: Harvard Business Review Press, 2025. ISBN 978-1647827175.
- [2] Roettgen, R.: To Infinity: The New Space Economy, □ independently published, 2024. ISBN 979-8864261378.
- [3] SpaceX: Capabilities and Services Falcon 9. URL: <https://www.spacex.com/vehicles/falcon-9/>, accessed 15.04.2025.
- [4] Hall, D. L.; McMullen, S.: Mathematical Techniques in Multisensor Data Fusion. Artech House, 2004. ISBN 978-1580533355.
- [5] Asquith, C. F.: Weight selection in first-order linear filters. Technical report. Army Inertial Guidance and Control Laboratory Center, Redstone Arsenal, Alabama, 1969. DOI: 10.21236/ad0859332.
- [6] Tenne, D.; Singh, T.: Optimal Design of α - β -(γ) Filters. In: Proceedings of the American Control Conference, 2000. DOI: 10.1109/ACC.2000.877043.
- [7] Welch, G.; Bishop, G.: An Introduction to the Kalman Filter, University of North Carolina at Chapel Hill, 2006.
- [8] Kalman, R. E.: A New Approach to Linear Filtering and Prediction Problems, Transaction of the ASME. In: Journal of Basic Engineering (1960), pp. 35-45.
- [9] MATrix LABoratory: Kalman Filter. URL: <https://www.mathworks.com/discovery/kalman-filter.html>, accessed 15.04.2025.
- [10] Zhang, H. et al.: An updated method for digital twin multi-dimension models. In: Robotics and Computer-Integrated Manufacturing 80 (2023).
- [11] Stanciu, R.; Oh, P. Y.: Human-in-the-loop camera control for a mechatronic broadcast boom. In: IEEE/ASME Trans. Mechatron (2007) 12, pp. 41-52.
- [12] Khan, J.; Kim, K. A.: Performance Evaluation of the Alpha-Beta (α - β) Filter Algorithm with Different Learning Models: DBN, DELM, and SVM. In: Appl. Sci. (2022) 12, p. 9429.
- [13] Khan, J. et. al.: An Improved Alpha Beta Filter Using a Deep Extreme Learning Machine. In: IEEE Access 9 (2021), pp. 61548-61564. DOI: 10.1109/ACCESS.2021.3073876.
- [14] Phyo, P. P.; Jeenanunta, C.: Daily Load Forecasting Based on a Combination of Classification and Regression Tree and Deep Belief Network. In: IEEE Access (2021) 9, pp. 152226-152242.
- [15] Fayaz, M.; Kim, D.: A prediction methodology of energy consumption based on deep extreme learning machine and comparative analysis in residential buildings. In: Electronics (2018) 7, p. 222.
- [16] Lewis, R. J.: An introduction to classification and regression tree (CART) analysis. In: Proceedings of the Annual Meeting of the Society for Academic Emergency Medicine, San Francisco, CA, USA, May 22-25, 2000; Volume 14.
- [17] Osuna, E.; Freund, R.; Girosi, F.: An improved training algorithm for support vector machines. In: Neural Networks for Signal Processing VII, Proceedings of the 1997 IEEE Signal Processing Society Workshop, Amelia Island, FL, USA, September 24-26, 1997; IEEE: Piscataway, NJ, USA, 1997; pp. 276-285.



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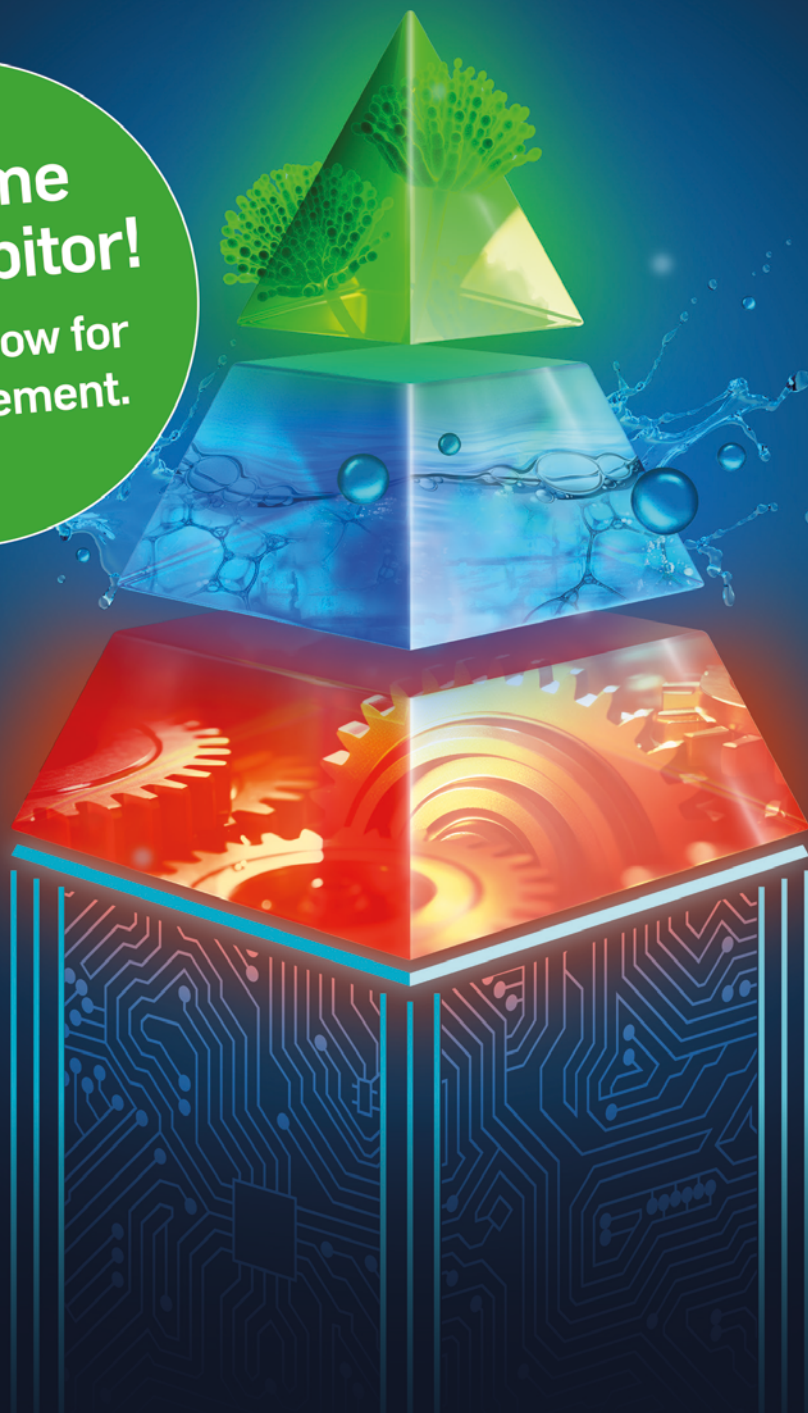
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“Entrepreneurial courage is the key ingredient”

Interview with Prof. Jan Wörner, Director of the Frankfurt Institute for Advanced Studies (FIAS)

Production is leaving Earth. As access to space becomes increasingly affordable and reliable, the idea of manufacturing in space, once the stuff of science fiction, is evolving into a real industrial strategy. In this interview, Jan Wörner, who has headed not only the German Aerospace Center (DLR) for many years, but also the European Space Agency (ESA), talks about strategic opportunities and regulatory challenges.

Production in space—are we really as far along as some visions have us believe?

“What sounds like a fairy tale today may be reality tomorrow.” That motto brought the German cult series *Raumpatrouille* to life in 1966. In fact, various “products” have already been manufactured in space at zero gravity. Just take these two examples: the cultivation of grapevines that are resistant to mildew and high-purity glass fibers.

From a civil engineer’s point of view, what value can extraterrestrial production add?

Civil engineers are only needed here in a secondary role. The aim is to make targeted use of weightlessness to manufacture new products, such as medicines. Incidentally, the International Space Station (ISS) is an example of a structure built in space: it would have been impossible to build the entire structure on Earth and then transport it to space. Interestingly, the individual components of the ISS “met” for the first time in space. This fact is significant insofar as we often experience problems on Earth when assembling different components. Such problems must be avoided in space through appropriate planning and execution.

Which innovations from space production could have a particularly rapid impact on terrestrial construction and manufacturing processes?

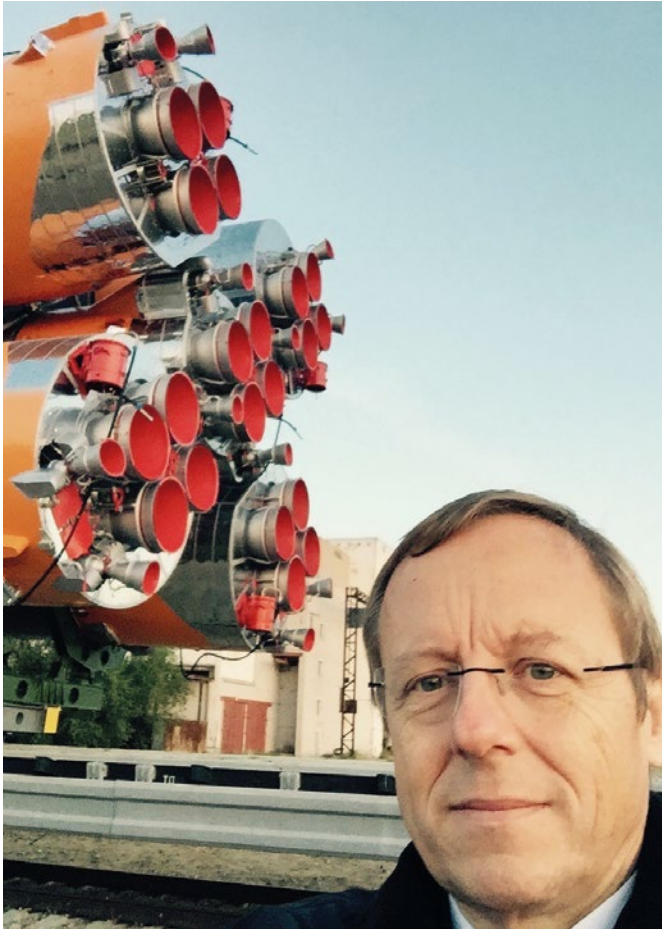
If one could formulate a comprehensive answer to this question, the fascination of innovation through curiosity and chance would have already been demystified a long time ago. In fact, it has been shown that novel approaches and activities have always produced unpredictable aspects, or “side effects,” so to speak. Who would have thought that tracking Sputnik in 1957 could lead to the development of a global satellite navigation system that now plays a key role in construction? I prefer to quote from Steve Jobs: “Stay hungry, stay foolish.”

How well are German companies—especially those in the mechanical and plant engineering sector—prepared for potential synergies on the threshold of orbit?



Jan Wörner

Born in Kassel in 1954, Jan Wörner is a civil engineer and was Chairman of the Executive Board of the German Aerospace Center (DLR) from 2007 to 2015 and Director General of the European Space Agency (ESA) from 2015 to 2021. After his studies at the Technical University of Darmstadt, including a year-long research visit in Japan, he became a professor and later its president. Wörner has received honorary doctorates from universities worldwide, is a member of several science academies, and has been awarded the Federal Cross of Merit (Bundesverdienstkreuz) and the French Legion of Honor for his services to science and education. Jan Wörner is married and has three adult children who work in various fields: quantum technology, automotive engineering, and architecture. His hobby is repairing and restoring old cars.



Jan Wörner with the engines of the Soyuz-FG launch vehicle.

Clearly in Germany, too, a number of companies, especially SMEs and start-ups, are not just passively following the topic, but are actively developing opportunities. In this context, the continued, exorbitant costs of orbital logistics remain a major obstacle.

Is the space economy a domain for global players—or does it present a historic opportunity for German SMEs as well?

The space economy is fascinating because it transcends national borders. Time and again, space travel opened up opportunities for cross-border cooperation. The balance between national activity and global cooperation is a necessity for any activity. The opportunities are real—they just need to be seized courageously.

How substantial are the ESA’s capacities and ambitions in the areas of space manufacturing and space exploitation?

Space manufacturing has so far played a minor role in institutional funding. This is reasonable, as it is primarily of commercial interest. In contrast, exploitation plays a crucial role in the ESA’s Exploration program, particularly by drawing on the International Space Station.

What needs to happen—institutionally and entrepreneurially—to boost economically and ecologically sensible space development?

Entrepreneurial courage is the key prerequisite. At the institutional level, development projects can help to build certain competencies. At the same time, care must be taken to ensure that this institutional support does not degenerate into the financing of commercial activities mired in micromanagement.

Is there such a thing as “sustainability” in space at all—and if so, how should it be conceptualized and regulated?

When space travel began in 1957 with Sputnik, no one could have imagined its present scale, and what it will reach in future. There is a clear need to consider the issue of “sustainability” in space as well. That involves many aspects, such as “clean” rocket propulsion, the reusability of rockets and satellites, and the avoidance of space debris.

Could space even act as a catalyst for a more resource-efficient industry on Earth—e.g., through closed cycles or innovative materials?

Space travel has always been a catalyst of innovation. It is highly desirable that this capability be extended to the issue of sustainability. Space travel already has a lot to offer in terms of resource efficiency, as the laws of gravity require the development of structures that are as light as possible.

What is more strategically important in the long term: the further development of AI or the establishment of orbital production capacities—or are the two issues inextricably linked?

Is agriculture or medicine more important? We should avoid pitting different and promising aspects against each other. We need AI and we need opportunities for activities in zero gravity, even after the ISS. The frequently cited argument of financial prioritization isn’t helpful either: In Europe, the costs of institutional space travel amount to 15 euros per citizen per year. This is certainly not an amount that normally would incite individuals to think about prioritization. We need AI, we need space travel, we need research, we need social development. And for all of that, we need peace and freedom.

Ten years from now, where will we be in terms of space production, and what will (still) be science fiction?

Ten years can change a lot or very little. My hope is that in ten years, an ecosystem will have emerged in which many companies have not only discovered the opportunities of sustainable production in space but have also achieved them.

What fascinates you most about the idea that in the future, humans will not only produce in space, but for space as well?

I have been a space nerd since the 1960s. As Director General of the ESA, I have learned plenty about the many fascinating aspects of space travel. Today, I can already see that production and development in zero gravity are leading to highly innovative products. The future will see a new system of activities involving humans and robotic systems. Humans in space will remain important, not only as subjects of medical research, but also as innovators

who can inspire others, especially young people. At the same time, robotics is developing rapidly, not least thanks to the possibilities of AI, and can certainly perform essential tasks in space logistics, including production in space.

Dear Prof. Wörner, thank you very much for your insights!

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Maria Birlem

Organs from Space

How weightlessness could change human lives





Due to its weightlessness, space offers enormous opportunities for production. The unique conditions of microgravity, for example, can simplify the development of organs and tissues from the body's own stem cells, allowing therapies to be developed in a more targeted manner. Even though many independent initiatives are currently emerging to explore this and other potential applications, their success is not a foregone conclusion. The success of a thriving space economy, especially in Europe, also requires smart policies that understand how to develop the right framework conditions.



Maria Birlem, co-founder and CEO of Yuri, with Dorothee Bär, Federal Minister of Research, Technology, and Space (BMFTR).

Severe congenital heart defects, such as those that can occur in premature babies, often lead to long-term and complex treatments. These include repeated operations, long-term medication, limited physical abilities, and an overall significantly reduced quality of life. In many cases, the only option is an organ transplant.

In Germany and Europe, thousands of patients are waiting for a donor organ, while the number of available organs has for years fallen significantly short of actual medical demand. Cardiological and other diseases further complicate the situation, as considerable challenges remain even after a successful transplant. The immune system recognizes the transplanted organ as foreign, which can lead to rejection. To prevent this, those affected must take immunosuppressive drugs for the rest of their lives, which protect the organ but are sometimes associated with significant side effects. In addition, the functional life of donor organs is limited. A transplanted heart typically lasts about ten to 15 years or slightly longer in the best case.

A concrete example illustrates this problem: A boy with a complex congenital heart defect requires several cardiac surgeries in early childhood. In adolescence, his condition

deteriorates to such an extent that he must be permanently monitored in the hospital and connected to medical support systems. Only after a long wait does he receive a suitable donor heart. The transplant is successful, but the long-term limitations remain—lifelong immunosuppression and a limited organ lifespan. This example is not an exception, but rather a structural problem in transplant medicine.

Patient-specific organs from stem cells as a vision

A central research approach in modern regenerative medicine is the use of the patient's own stem cells to generate tissue or entire organs in future. The goal is to provide patient-specific, immunologically highly compatible organs in the long term, minimize rejection reactions, significantly reduce the need for immunosuppression, and make the availability of organs independent of the number of donors.

Various technologies are combined to achieve this objective. Induced pluripotent stem cells, i.e.,

reprogrammed body cells, serve as the starting material and can be differentiated into different tissue types. 3D bioprinting makes it possible to introduce cells into defined spatial structures and thus build complex tissue arrangements in a targeted manner. Organoids, i.e., miniaturized, organ-like tissue structures, form an important intermediate stage in this process. Although they are not yet fully functional organs, they replicate essential characteristics of the corresponding organ and are already suitable for more precise drug testing and active ingredient screening—especially when they are generated specifically for a patient and thus represent the tissue of a specific individual. The great medical dream is to eventually use these technologies to develop fully functional, transplantable organs that are tailored precisely to the individual patient.

Gravity, vascularization, and the technical limitations of Earth

On Earth, the production of complex, functional tissue structures face two key physical and biological hurdles. On the one hand, gravity causes soft, freshly printed cell constructs to deform or collapse under their own weight. To prevent this, support structures known as scaffolds are used. These scaffolds must later be biodegraded or removed without damaging the tissue. This process is technically demanding and not always fully controllable, which can impair both the function and stability of the tissue.

On the other hand, vascularization, i.e., the formation of a finely networked vascular system, is one of the greatest challenges. A functional organ requires a dense network of blood vessels to supply oxygen and nutrients and remove metabolic waste products. The formation of stable, functional blood vessels in three-dimensional structures has so far only been achieved to a limited extent on Earth. Especially in thicker tissues without sufficient perfusion, oxygen deficiency, cell death, and loss of function can occur quickly. At present, these limitations slow down the development of fully functional, transplantable organs from bioprinters and make it clear that new environmental conditions and approaches are needed.

Why microgravity can have such a big impact

Microgravity in near-Earth orbit fundamentally changes the boundaries for biological processes. In this environment, gravity has virtually no effect, structures collapse significantly less, and cells can organize themselves more homogeneously in three dimensions.

Transport processes such as diffusion and convection, as well as cell-cell interactions, proceed differently than on Earth and can promote certain biological developments. Experiments with tissue and organoids in microgravity have shown that three-dimensional structures can grow more stably and require less extensive support structures.

There is also evidence that microgravity improves the tendency to form small blood vessel networks and that organoids are more prone to vascularization than under conditions on the Earth's surface. From a technical point of view, low Earth orbit is particularly interesting. It can be reached relatively quickly, requires less energy than higher orbits, and already has infrastructure in place, such as the International Space Station and, in future, new commercial space stations. This makes space a potentially ideal laboratory environment for complex bioengineering and opens up a new approach to overcoming the existing limits of tissue production on Earth.

From stem cells to tissue in orbit

To realize the production of individualized organoids and, in the long term, organs in space, an integrated system is required that encompasses all steps from cell procurement to the return of tissue to Earth. First, patient-specific stem cells are obtained on Earth and multiplied under controlled conditions. These cell populations are standardized, characterized, and quality assured to create a reproducible starting point for the subsequent steps. The cells, culture media, and reagents are then transported into orbit. Temperature and environmental conditions must be maintained in accordance with applicable quality

Commercial LEO Destinations

Commercial LEO Destinations is a NASA program to develop privately operated space stations in low Earth orbit to replace the ISS when it is decommissioned as scheduled. Instead of financing a new station itself, NASA is relying on commercial providers from whom it will purchase research and usage services in future. The program promotes innovation, reduces costs, and enables new applications in space—from science and industrial production to logistics and tourism. Several companies are currently developing modular, reusable stations designed to create a diverse and competitive infrastructure in low Earth orbit

and safety standards, which should be close to GMP requirements.

In orbit, biological laboratory units designed for operation in microgravity are then used in space stations or orbital platforms. A specialized 3D bioprinter adapted to this environment precisely deposits the cells and biomaterials to form organoids or more complex tissue structures. Automated media changes, integrated monitoring, and process control ensure a stable environment during the culture phase. In the subsequent maturation phase, the printed organoids or tissues are incubated in suitable bioreactors to promote the formation of functional structures, including vascularization. Once culture and maturation are complete, the samples are loaded into return capsules, transported back to Earth, analyzed in specialized laboratories, and evaluated for functionality and quality. In the long term, suitable tissues could eventually be transferred to clinical applications.



Maria Birlem

studied aerospace engineering at Aachen University of Applied Sciences from 2001 to 2005 and created a link budget as part of the Compass 1 CubeSat project. After graduating, she worked at DLR: in Berlin, she designed the launch electronics interface for the BepiColombo laser altimeter, and in Cologne, she was involved in ROSETTA/PHILAE and EXOMARS. In 2009, she joined ESA/ESTEC as a young graduate trainee and investigated the calibration of a laser communication telescope. She then joined Airbus Defence & Space, where she headed the “kiwi” microgravity program and managed projects such as MMARS-1/2, 3D PrintOS, V3PO, and BioScience-4. She was also Payload Integration Manager for ESA’s EMCS and Development Engineer for SIMBOX. Since 2019, she has been co-founder and CEO of Yuri GmbH.

The role of specialized actors: infrastructure and technology in LEO

This development requires specialized players who have mastered the technical and organizational aspects of research, development, and production in microgravity. Such companies or consortia typically offer flight-certified end-to-end services ranging from mission planning and execution to the logistics of transporting experiments and biological samples, integration into space systems, and returning the results to Earth. Access to laboratories in microgravity via existing platforms and future commercial LEO destinations enables experiments and production processes to be carried out in microgravity. At the same time, proprietary technologies for bioengineering in orbit such as complex 3D bioprinters are being developed, as well as automated culture systems designed for use in microgravity. The aim of these activities is to systematically explore the potential of bioengineering in microgravity, address the needs of industries such as pharmaceuticals, medical technology, materials science, and the nutrition and health sector, and develop viable business models. This proactively secured access to commercial LEO platform providers allows such players to position themselves early in an emerging market segment that encompasses the commercial use of near-Earth orbit for research and production.

Fields of application beyond organ transplantation

The production of individualized organoids and, later, organs in space opens up a wide range of possible applications that go far beyond traditional transplant medicine. In transplant medicine, patient-specific, transplantable organs could be produced in the long term, significantly reducing the risk of rejection and decreasing dependence on donor organs. Waiting lists could be shortened or eventually become obsolete, while the quality of life of those affected would improve considerably. In the field of individualized pharmacotherapy, patient-specific organoids enable the testing of active substances and therapeutic concepts directly on tissue that reflects the characteristics of the respective patient. On this basis, therapies could be selected and dosed more precisely, side effects could be reduced, and efficacy could be better predicted.

In toxicology and safety assessment, human organoids open up new possibilities for investigating the effects of substances in the cosmetic, chemical, or pharmaceutical sectors. Animal testing could be replaced or significantly reduced by human-relevant models, which would bring both ethical and scientific benefits. In addition, the use of

microgravity offers considerable added value for basic research, for example, in the study of cell behavior, tissue organization, regeneration processes, and signaling pathways in an environment with altered physical conditions. The knowledge gained there can be incorporated into new approaches for tissue engineering and regenerative therapies on Earth.

Europe in the strategic competition for near-Earth orbit

Low Earth orbit is increasingly evolving from a predominantly state-dominated research space to a commercial economic space. In addition to the established spacefaring nations, the US is investing heavily in commercial space stations, cost-efficient launch systems, and new business models in the areas of in-orbit servicing and in-orbit production.

Although Europe has an excellent research landscape, a high level of space expertise, and numerous innovative companies, it has so far only built up a limited amount of its own independent infrastructure in low Earth orbit. Investment strategies are often cautious, regulatory frameworks are complex, and risk appetite is limited.

If Europe wants to be more than just a user of space biotech and production in space, but also a shaping player, targeted measures are needed. These include investments in European LEO infrastructure, the promotion of demonstration missions with clear commercialization prospects, and framework agreements that offer companies a reliable basis for planning. At the same time, a regulatory environment is needed that supports

innovation, accelerates processes, and facilitates cooperation between space, medicine, biotechnology, and industry.

A future market with huge potential – not only for patients

The combination of stem cell technology, 3D bioprinting, and microgravity opens up new technological opportunities for transplant medicine and biomedicine as a whole. Individualized organs made from the patient's own cells have the potential to significantly reduce dependence on donor organs, minimize rejection reactions, improve the quality of the patient's life in the long term, and make therapies more precise and safer. At the same time, animal testing can be replaced or reduced in many areas by models relevant to humans.

The first building blocks on the way to achieving this have already been implemented: end-to-end services for research and production in microgravity, secure access to commercial LEO platforms, and the development of specialized 3D bioprinters for use in orbit.

The next steps include validating the technology in iterative missions, transferring the results to medical and industrial applications, and at the same time shaping the framework conditions in Europe to allow for the emergence of a viable market for space biotech and production in space. In the long term, this could lead to a situation in which a young person with a serious organ disease is no longer dependent on a donor organ from another person, but receives an organ created from their own cells – possibly produced in an orbital production facility in low Earth orbit.

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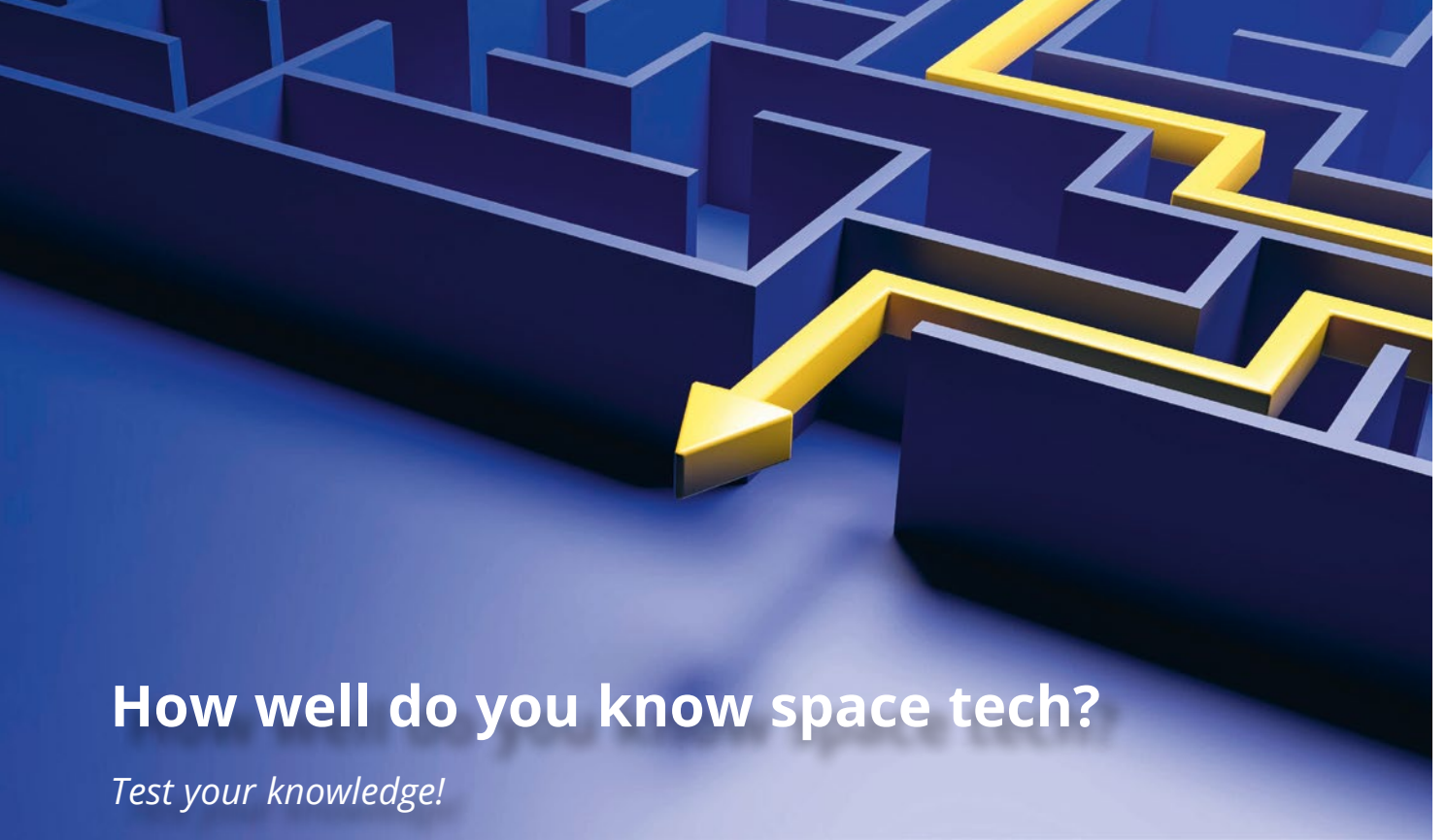
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How well do you know space tech?

Test your knowledge!

- 1. What factor currently poses the greatest obstacle to the widespread use of natural building materials such as wood and clay in industrial construction?**
 - A) Lack of standardization and normalization for structural applications
 - B) Low compressive strength under changing climatic conditions
 - C) Excessive energy intensity in material processing
 - D) Lack of acceptance among architects
- 2. What is the primary goal of digital knowledge platforms in an industrial or scientific context?**
 - A) The complete automation of innovation processes without human involvement
 - B) Centralized storage of large amounts of data to reduce IT costs
 - C) The structured collection, networking, and provision of knowledge to promote innovation and cooperation
 - D) The creation of proprietary software solutions for knowledge retention
- 3. What technical advantage makes hydrogen fuel cells particularly interesting for use in intralogistics?**
 - A) The ability to provide electrical energy without charging times through a quick refueling process
 - B) Significantly higher peak performance compared to lithium-ion batteries with the same mass
 - C) Complete independence from oxygen during energy generation
 - D) The direct use of fossil hydrogen as an energy source without emissions
- 4. What potential do large language models (LLMs) offer for operational knowledge management?**
 - A) They can automatically generate new scientific findings without drawing on existing knowledge
 - B) They enable the semantic capture, structuring, and condensation of implicit knowledge from text-based sources
 - C) They completely replace traditional databases with neural memory storage
 - D) They guarantee objective and error-free knowledge processing without human validation
- 5. Which characteristic is particularly crucial for robot systems when assembling and disassembling satellite components in orbit?**
 - A) Ability to autonomously adapt gripping and movement strategies to changing object geometries
 - B) High bandwidth for data transmission between ground station and robot
 - C) Minimal mass of robot grippers to reduce launch costs
 - D) Use of standard components from terrestrial industrial automation
- 6. What is the goal of applying circular principles in industrial production systems?**
 - A) Reduction of waste and resource consumption by returning materials to the production cycle
 - B) Maximizing production speed through linear process chains
 - C) Focusing on the end-of-life phase of products without influencing upstream processes
 - D) Substitution of natural raw materials with synthetic alternatives to simplify material logistics

7. What is the advantage of using digital knowledge platforms in international research networks?

- A) Complete elimination of cultural differences in collaboration
- B) Accelerated knowledge transfer through structured data exchange and communication mechanisms
- C) Replacement of physical research laboratories with virtual simulations
- D) Avoidance of regulatory requirements in cross-border data exchange

8. What is the main difference between fuel cell and battery technologies in terms of their energy supply in industrial applications?

- A) Fuel cells continuously convert chemical energy into electrical energy, while batteries discharge stored energy
- B) Batteries generate energy from hydrogen, while fuel cells store electrical energy directly
- C) Fuel cells only work efficiently at very high temperatures, while batteries only work efficiently at low temperatures
- D) Batteries can be charged an unlimited number of times, whereas fuel cells can only be used once

9. What is the advantage of additive manufacturing in space?

- A) Lower maintenance costs for on-board computers
- B) Higher gravity facilitates material processing
- C) Ability to manufacture spare parts directly on site and save on transport costs
- D) Better radio transmission between production modules

10. What property must a material have for use in orbital production?

- A) High thermal conductivity and electrical insulation
- B) Biodegradability
- C) Magnetizability for better positioning
- D) Radiation resistance and dimensionally stable microstructure during temperature changes

11. Which challenge is particularly critical for robotic gripping systems in satellite maintenance?

- A) Excessive friction in the atmosphere
- B) Unstable communication with ground stations
- C) Insufficient power supply from solar cells
- D) Lack of reference points and variable surface structures of components

12. What distinguishes the life cycle of sustainable production systems from conventional approaches?

- A) Focus exclusively on the production phase
- B) Holistic view from raw material extraction to recycling
- C) Minimization of energy consumption during transport
- D) Exclusive use of digital twins

13. What is the goal of the concept of “human-centric automation” in Industry 5.0?

- A) Complete automation of all production processes
- B) Transfer of human tasks to AI systems
- C) Integration of humans as decision-makers in adaptive, collaborative systems
- D) Reduction of human intervention to emergency measures

14. Why is knowledge management crucial for the operation of complex space missions?

- A) To avoid redundancies in hardware
- B) Because explicit and implicit knowledge must be retained for maintenance, safety, and error analysis
- C) To reduce communication latencies
- D) To control energy flows in the satellite

15. What is the advantage of using AI-based simulations in space production?

- A) Prediction of material behavior and process deviations under space conditions
- B) Reduction of radio traffic to Earth
- C) Compensation for energy losses through algorithmic control
- D) Increasing radio bandwidth

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Strategic Implications of the Draft EU Space Law

Overview of key aspects

- Space is increasingly recognized as an important economic, technological, and political domain with civil and military implications.
- The space industry is transforming from a state-controlled to a commercial industry ("New Space") and hence requires a clear and harmonized legal framework.
- The EU has published a draft space law to regulate and support the growing space sector which is expected to reach a volume of US\$1.8 trillion over the next ten years.
- Implementation is planned for January 1, 2030, providing sufficient time for national adjustments and technical preparations.
- As an EU regulation, the law applies directly in all member states, but it requires supplementary national legislation.
- The overarching strategic objectives include strengthening the EU's space sovereignty, securing access to critical infrastructure, and enhancing its position in global space competition.
- The regulation thus aims to reinforce Europe's global competitiveness and strategic autonomy in space technologies and services.
- Its framework is based on three core pillars: safety (technical and operational standards), resilience (cybersecurity and threat response), and sustainability (long-term environmental and operational responsibility).
- The primary regulated domains include space activities (such as launches and operations) and space services (such as satellite-based applications).
- National authorities are tasked with licensing and registration and transmit the relevant data to the Union Register of Space Objects (URSO).
- Qualified Technical Bodies (QTBs), comparable to TÜVs, are designated to verify the missions' technical and safety compliance.
- The European Union Agency for the Space Program (EUSPA) will be given broader responsibilities, including data management, compliance monitoring, and cybersecurity coordination.
- The regulation contains detailed technical requirements, covering collision avoidance, space debris reduction, standardized material use, and data interoperability.
- Risk assessments, life-cycle analyses, and robust cybersecurity frameworks are mandatory for all operators.
- Sustainability measures require full documentation of each mission's environmental footprint, including component manufacturing and supply chain impacts.
- A new European Union Space Resilience Network (EUSRN) will coordinate cyber resilience efforts across EU institutions and member states.
- The free movement of space data constitutes a core principle, with national restrictions permitted only under exceptional circumstances.
- While the regulation recognizes the important role of SMEs in fostering innovation, the current mechanisms remain limited.
- International cooperation is identified as essential to prevent national fragmentation and ensure global interoperability.
- Non-EU providers must meet additional conditions and cooperate with EU institutions on registration and compliance.
- The regulation aims to balance national interests by promoting an integrated EU-wide space ecosystem.
- National political commitment - particularly in larger member states such as Germany - will be crucial for successful implementation. Yet, several legal gaps remain, including the issue of liability for private space actors.

For more information, click here



European Commission: EU Space Act. 2025.
URL: https://defence-industry-space.ec.europa.eu/eu-space-act_en

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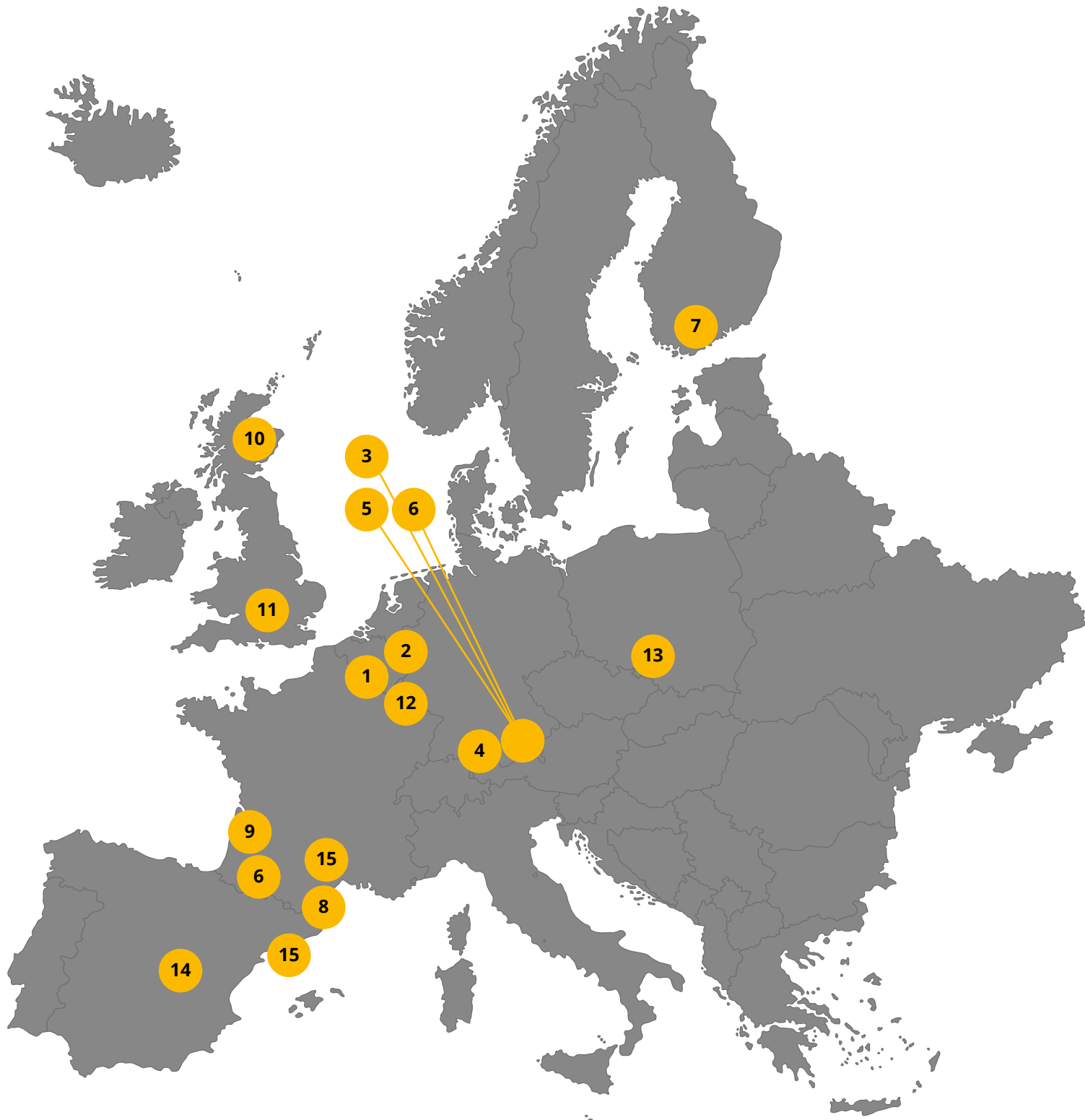


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9

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14

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Atmos Space Cargo

Munich, Germany

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Orbex

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15

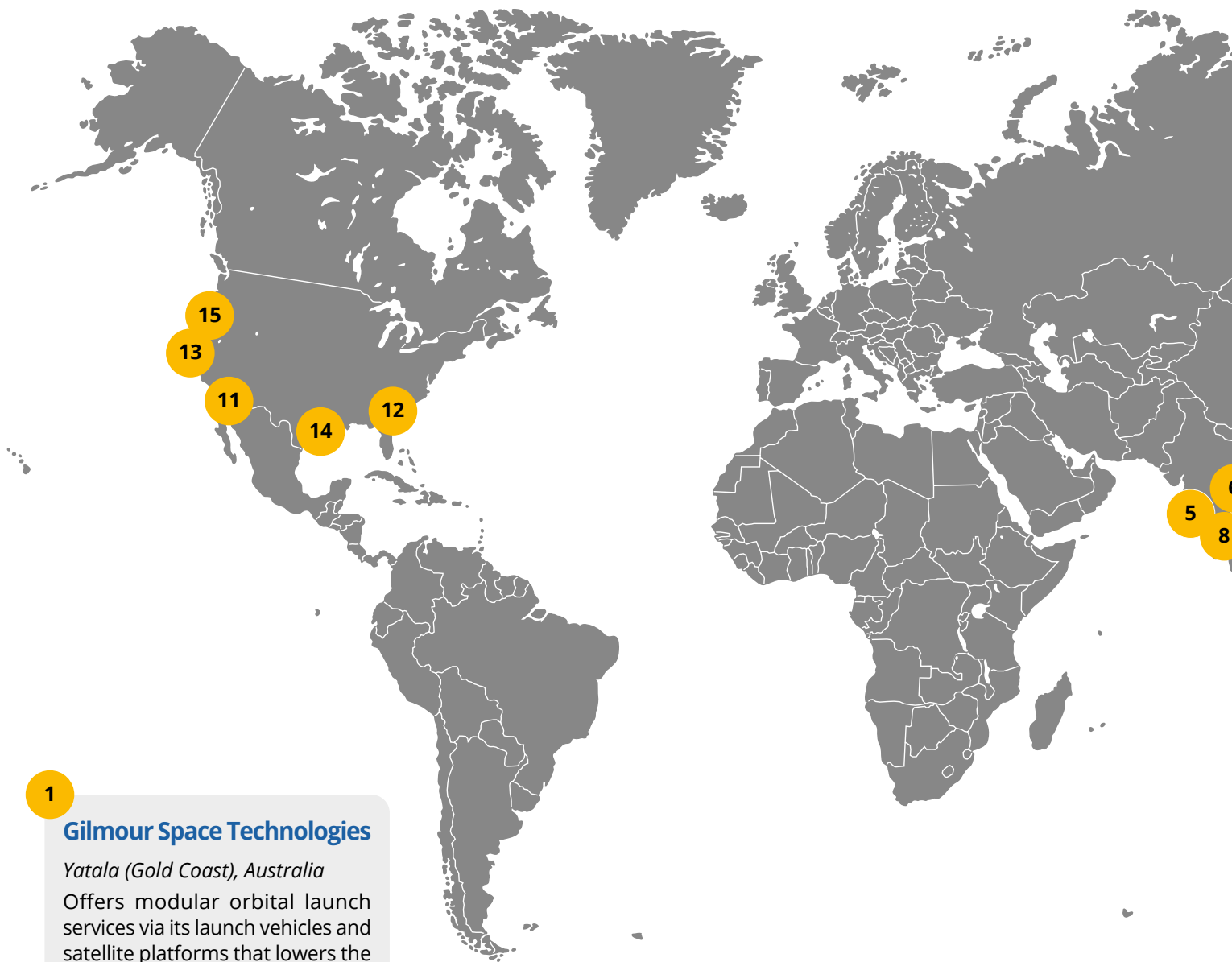
Pangea Aerospace

Barcelona/Toulouse, ESP/FR

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www.pangeapropulsion.com

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1

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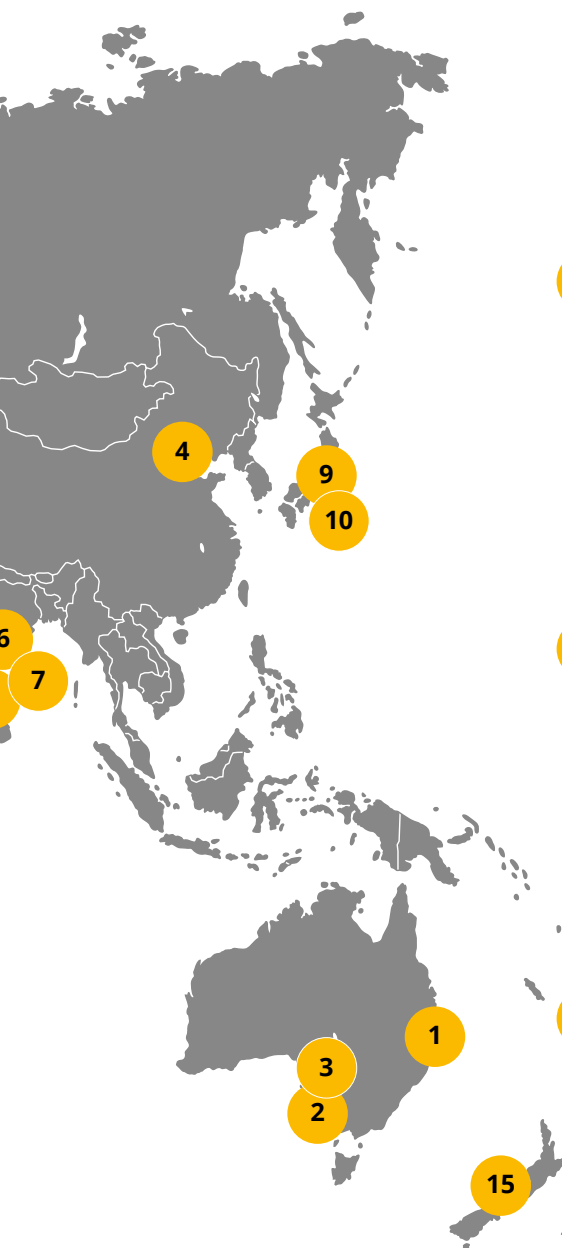
4

LandSpace

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6

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Potentials, Premises, Perspectives

Generative AI, including large language models (LLMs), is developing rapidly and steadily penetrating more areas of society. Against the backdrop of demographic change, the question arises as to whether LLMs can support knowledge management in companies. One thing is clear: the loss of implicit knowledge that is not documented and difficult to communicate could pose an existential risk to the manufacturing industry in the near future.

Keywords

large language model, generative artificial intelligence, knowledge management, tacit knowledge, knowledge elicitation, expert interview



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Potentials, Premises, Perspectives

Using LLMs to reinterpret corporate knowledge management

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Demographic change is exacerbating the shortage of labor and skilled workers in the manufacturing industry, making knowledge management an increasingly important issue in many companies. Collecting and preserving tacit knowledge poses a particular challenge. This study examines the extent to which large language models (LLMs) can provide meaningful support in knowledge gathering through expert interviews. Three experts test and evaluate a personalized chatbot that has been developed using ChatGPT-5. The results of the interview are promising, but the summary shows room for improvement.

German industry is facing profound change due to a rapidly aging population. Studies predict that by 2036, around 19.5 million of the current 45.6 million employed people in Germany will retire [1, 2]. That not only aggravates the already prevailing shortage of skilled labor, but also provokes a loss of experience-based knowledge. As a result, companies in the manufacturing sector are increasingly confronted with the challenge of preserving the knowledge of seasoned employees. Particularly critical in this context is the loss of tacit knowledge—knowledge that is not documented and yet essential for operational excellence. The rapid development of generative artificial intelligence, especially large language models (LLMs), opens up new avenues for systematically capturing, accessing, and efficiently utilizing such knowledge [3]. This study aims to develop an initial concept for a practice-oriented, LLM-based knowledge management system that specifically addresses and evaluates the preservation of tacit knowledge.

Tacit and explicit knowledge

According to Ackoff's knowledge pyramid (1989), knowledge represents the highest level of abstraction above data and information [4]. Knowledge is considered particularly critical when it is tacit [4]. Alavi and Leidner (2001) define

tacit knowledge as skills that are difficult to communicate and deeply embedded in individual routines and thought patterns [5]. In English-language literature, tacit knowledge is distinguished between "tribal," "tacit," and "implicit knowledge" [6]. A

comprehensible differentiation between the terms is elaborated in [6]. "Tribal knowledge" describes the practical knowledge of (long-standing) employees that is necessary for internal processes. The knowledge acquired by experts through practical, real-world experience ("best practices") is "tacit knowledge." And "implicit knowledge" includes cultural knowledge such as traditions and values. Since the study focuses on preserving the experiential knowledge of production employees, tacit knowledge is considered in the sense of "tacit knowledge" and "tribal knowledge."

Explicit knowledge, for example, work instructions or technical documentation, can be stored and transferred more easily [7]. However, even explicit knowledge frequently loses its applicability and usefulness without the context of tacit reference [8]. Therefore, the preservation and transfer of tacit knowledge are particularly critical.

The challenges of technological knowledge management in industry can be divided into three key barriers: social, technical, and organizational factors [3, 9]. At the social level, for example, a lack of motivation, low recognition for knowledge transfer, or fear of losing significance may disincentivize knowledge sharing. At the technical level, there is often a lack of user-friendly, accessible systems for documenting and retrieving knowledge. At the organizational level, industrial practice often lacks strategic anchoring, formal processes, and internal responsibilities for knowledge retention [3, 10, 11]. This initial study aims to examine the use of LLMs as a tool for collecting tacit knowledge as a possible solution to these technical and organizational challenges.

Elicitation of tacit knowledge

This paper focuses on the elicitation of tacit knowledge. In [12], various methods of knowledge elicitation are collected and compared using a literature analysis. When



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selecting methods, it is assumed that a combination of different methods is usually needed to capture knowledge holistically. By combining different methods, the weaknesses of individual methods can be compensated [12, 13]. Unstructured and semi-structured interviews in combination with observation are identified as particularly suitable for eliciting tacit knowledge [12]. Interviews are the most commonly method for knowledge elicitation [13]. Observation can be used to capture knowledge that cannot be expressed or is difficult to communicate verbally [12, 13]. Interviews are chosen as the method of knowledge elicitation for this study.

According to Shadbolt et al. [13], interviews can be divided into structured, semi-structured, and unstructured interviews. Unstructured interviews have no fixed sequence and no thematic boundaries. This form of interview provides an overview of the topic and the interviewee can co-determine the focus of the conversation. In contrast, structured interviews follow a fixed structure and use predetermined questions, e.g., “Could you tell me about a typical case?” or “Why would you do that?”. This structure facilitates the subsequent evaluation of the interview and ensures that only thematically important issues are discussed, thus increasing efficiency. One disadvantage of the fixed structure is that topics may be overlooked, especially when conducting an initial overview. [13]

LLMs as a tool for knowledge elicitation

Current technological advances in generative artificial intelligence, particularly LLMs, promise a profound transformation of operational knowledge management [14]. LLMs such as OpenAI, Inc.’s GPT are based on huge training datasets and can understand and generate human-like language [15, 16]. This opens up new means of capturing, structuring, and contextualizing knowledge [17, 18]. Such systems enable low-threshold collection of experiential knowledge—e.g., via voice-to-text applications.

Despite technological advances, challenges remain in implementing LLMs for preserving tacit knowledge in an industrial context. These include, among others:

- a lack of validation mechanisms, as LLMs do not have inherent logic checking [17]
- data protection and security issues when integrating company-specific content [19]
- acceptance problems at employee level due to skepticism or technical overload [20]
- unclear responsibilities for maintaining and using the knowledge base [16]

For the successful use of LLMs to collect tacit knowledge, it is vital to design these systems so that they not only function flawlessly in technological terms, but are also easy to use and designed with the user in mind [3].

During this study, the reliability and quality of knowledge elicitation will be assessed in advance using an LLM as an example. The research question of the extent to which LLMs can support the above-mentioned technical and organizational challenges will therefore be answered. The study does not yet explicitly include verification with other knowledge sources or a discussion of the necessary technical and social framework conditions, such as data security.

Related study

Van den Bent et al. [21] also investigates whether LLMs are suitable for knowledge elicitation. In the study, the knowledge elicitation process consists of an unstructured interview and subsequent ontology creation. An ontology is a method for conceptualizing knowledge and consists of classes, relations, rules, and instances [22]. The duration of the interview and the behavior of the LLM during the interview, as well as the results of ontology creation, are compared with human experts’ results. The study concludes that interviews using OpenAI’s LLM GPT-4 are more structured than interviews conducted by real people and therefore can yield efficiency gains. However, the study identifies poorer results in terms of ontology creation. For example, it was found that during ontology creation, the LLM supplements information that is not mentioned in the interviews. Some of this information is factually correct and therefore presumably originates from the LLM’s training data [21]. The present study uses a different methodology than that of van den Bent et al. [21].

Knowledge elicitation through interviews and summarization

During this initial study, a personalized chatbot was developed using OpenAI’s ChatGPT-5 (released in August 2025) that can conduct interviews on any topic with real people. A more recent LLM from the same provider as the related study described above is used.

The aim of the interviews is to gather tacit knowledge from the interviewee. The interviewees should be able to steer the interview thematically but without deviating from the topic and answer specific questions for further clarification. For this reason, semi-structured interviews are chosen for the study. In contrast to the related study, in which an ontology is created, the results of the interview in this study are output in a structured text file after the interview.

Summary	
Completeness	In your opinion, does the summary contain all the information mentioned by the interviewee?
Relevance	In your view, have all the unimportant peripheral topics and comments from the interview been successfully filtered out?
Redundancy	How many duplicate mentions does the summary contain?
Input Fidelity	From your perspective, does the summary contain only information from the interview, without any additional information?
False Information	Is the false statement from the interview included in the summary?
Clarity	In your opinion, is the summary also written in a way that is understandable for people without the relevant specialist knowledge?
Interview	
Duration	How many minutes does the interview take when using ChatGPT's "Voice Mode," measured from the start of the first interaction to the end of the summary?
Breadth	From your perspective, have all subtopics been discussed?
Depth	Did the chatbot ask questions often enough until, in your opinion, all the knowledge on the subtopics discussed had been shared?
Conversation Atmosphere	In your view, did the chatbot create a pleasant conversation atmosphere?

Figure 1: Evaluation criteria.

This summary could then be integrated as a document straight into a knowledge database.

When creating the chatbot, the rules of prompt engineering and the procedure for semi-structured interviews are considered. For this purpose, the role, goal, background information, procedure, and response format are specified. In-depth questions are also integrated into the system prompt as examples. To optimize the system prompt and thus the interview behavior, 15 interviews are conducted, and the system prompt is adjusted after each interview using another chatbot (based on ChatGPT-5). For this purpose, the interviews are reviewed in terms of conversation management and summarization, and if the behavior is inadequate, the correct procedure is specified in more detail in the system prompt.

For the evaluation, three experts are interviewed about nine different topics within the area of production-related innovations and processes. The experts, who are all engineers and experienced with LLMs and production,

select the topics. The interview begins with the expert naming the topic, which is then explored in greater detail using questions that the chatbot has tailored to the topic. In contrast, the related study only includes one expert and one topic area. As with [21], a distinction should be made between the evaluation of the interview and the final result, i.e., the summary. The evaluation criteria, including explanations, are shown in **Figure 1**.

To ensure that the duration of the interviews is comparable, all experts use ChatGPT's "Voice Mode."

In the study [21], it was noticed that all ontologies created by the LLM contain hallucinated information. The criterion of input fidelity is intended to verify this finding. Information in the summary that does not originate from the interview is considered a negative rating for input fidelity. The criterion of misinformation is introduced as an extension. For this purpose, the interviewee deliberately make a false statement in each interview. The chatbot aims to collect tacit knowledge without verification from other sources

Interview Overview (Experts and Topics)	Evaluation Criteria (evaluation scale (1-4) see below)											
	Interview				Summary							
	Duration (in min.)	Breadth	Depth	Conversation Atmosphere	Completeness	Relevance	Redundancy (number)	Input Fidelity	False Information (0 = not included, 1 = included)	Clarity (expert 1)	Clarity (expert 2)	Overall Clarity
Expert A, Topic: prompt engineering	10:26	3	4	4	4	4	4	4	1	3	3	3
Expert A, Topic: personalized chatbot	12:00	3	3		3	4	4	3	1	3	3	3
Expert A, Topic: requirements for a chatbot	8:27	2	4		3	4	3	2	1	4	3	3,5
Expert B, Topic: optical quality control	11:02	4	3	4	4	3	3	4	1	4	3	3,5
Expert B, Topic: circular economy, recycle system	13:30	3	3		2	3	0	4	0	3	3	3
Expert B, Topic: public funds	9:15	3	3		2	3	4	4	0	4	4	4
Expert C, Topic: manufacturing process "balancing"	8:23	4	4	4	3	4	2	4	1	4	3	3,5
Expert C, Topic: manufacturing process "shrinking"	6:27	4	4		3	4	1	4	1	4	4	4
Expert C, Topic: joining of car body panels	10:20	4	3		2	3	0	3	0	3	3	3
Average	9:58	3,33	3,44	4,00	2,89	3,56	2,33	3,56	0,67	3,56	3,22	3,39

Evaluation Scale (1-4): 1 = fully applies; 2 = somewhat applies; 3 = does not tend to apply; 4 = does not apply at all

Figure 2: Results table.

of knowledge, so that false statements should also be included. The reason for this is to potentially uncover new ideas and concepts by individual employees that are described in existing sources of knowledge using a different approach.

After their own interview, each expert evaluates it and the summary based on the criteria described. The experts then assess the clarity of the other candidates' summaries. The conversation atmosphere is evaluated by the expert after all their own interviews. The criteria of breadth, depth, atmosphere of the conversation, completeness, relevance, input fidelity, and clarity are evaluated subjectively, i.e., the expert chooses between "fully applies," "somewhat applies," "does not tend to apply," and "does not apply at all." For duration, the time is measured; for redundancy, the number of duplicate entries is counted; and for misinformation, it is checked whether the false statement is included in the summary.

An interview achieves better results than a summary

The results of the study are shown in **Figure 2**, and the average values of all criteria with the same rating (one to four) are shown in a bar chart in **Figure 3** for clear comparison.

The results of the study show that LLMs have plenty of potential when it comes to interviews. It's worth noting that the chatbot is better at asking in-depth questions than broad ones. Interviews last about ten minutes on average, so they don't take up too much time. The atmosphere surrounding the conversation also scores well. This helps counteract the employee acceptance issues mentioned above.

The values are more volatile in the summary. Completeness, in particular, only scores 2.89 points. As a result, some information from the interview is not included in the summary. Since the goal of the chatbot is to gather implicit knowledge, a complete summary is essential. The other

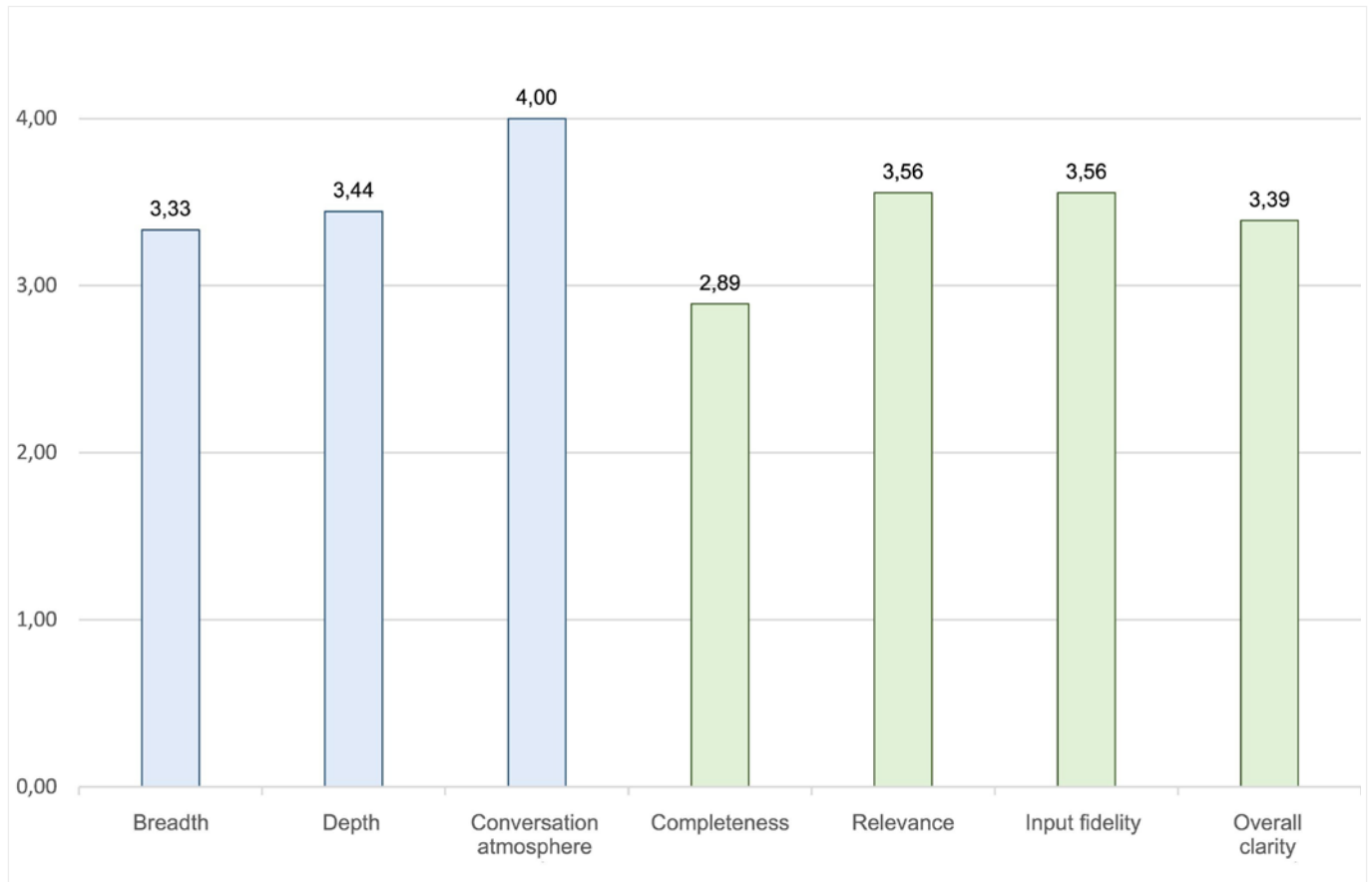


Figure 3: Bar chart with average values.

criteria for the summary achieve better results. The LLM seems to be able to filter out unimportant information to a large extent (relevance), and the summary is formulated in a way that is easy to understand—even for people who do not have the expert knowledge (clarity). However, as it is being incomplete, the result should be viewed in a more nuanced way. The summary contains hardly any irrelevant information, but some important information is also missing. Accordingly, it can be concluded that the chatbot is most likely unable to reliably distinguish between relevant and irrelevant information. On average, each summary contains 2.33 duplicate pieces of information (redundancy). However, total elimination of duplicate information is desirable.

Compared to the results from [21], the results for input fidelity and misinformation are more positive. One possible explanation for the improvement may lie in the use of a more advanced model and the different way in which results were output and presented. This, in turn, suggests that a summary constitutes a more suitable representation for collecting implicit knowledge with an LLM than an ontology. In most summaries, the LLM uses only information from the interview, and even factually incorrect information is included in six out of nine interviews.

Potentials and premises

This study was conducted approximately six weeks after the release of the ChatGPT-5 model. The interviewees described the conversation atmosphere as pleasant. In the evaluation, as the focus in creating the chatbot was on optimizing its interview behavior, the interview performed better than the summary. This result can be improved by increasing the number of preliminary interviews to optimize the system prompt. Moreover, the better performance regarding input fidelity and misinformation compared to the hallucination in the related study is also noteworthy. However, as mentioned in the previous chapter, these results should not be seen as universal. Especially in practical applications, the results for completeness in particular show potential for optimization.

Nevertheless, as this initial study demonstrates, LLMs, and ChatGPT-5 in particular, have great potential in the field of tacit knowledge elicitation. One approach may be the use of a human expert to check for consistency in the summarization process. This would also address the challenge mentioned at the outset, namely that LLMs lack an inherent logic check.

Perspectives for further research

This study provides research institutions with a starting point for further investigation into the subject and encourages companies to consider using LLMs when capturing implicit knowledge. In the future, we plan to conduct numerous additional interviews with external experts and to perform technology benchmarking with other LLMs. Interviews with experts who are not adept at using LLMs can help obtain more nuanced results. The results of our preliminary study fundamentally support a more advanced and programmatically more sophisticated prototype for preserving tacit knowledge in the production environment. This prototype will be tested, validated, and specifically optimized in various manufacturing companies while focusing on improving the interview output, i.e., the summary. Its aim is to preserve knowledge that would otherwise be lost due to demographic change and, at the same time, to strengthen the manufacturing industry's competitiveness in the long term. Besides being verified against other sources of knowledge, further studies will examine critical considerations such as data security and ethical issues. This initial study is limited to the technical and organizational challenges of capturing tacit knowledge.

Note from the authors to interested readers: As described, we are aiming to expand the database and conduct further interviews with external experts. If you are interested in the solution we have developed or would like to participate in further studies, we cordially invite you to contact us.

Bibliography

- [1] Deschermeier, P.; Schäfer, H.: The baby boomers are retiring. IW Short Report, No. 78, 2024. URL: <https://www.iwkoeln.de/studien/philipp-deschermeier-holger-schaefer-die-babyboomer-gehen-in-rente.html>, accessed on July 14, 2025.
- [2] Federal Statistical Office (Destatis): Press release No. 077 of February 28, 2025: Employment fell slightly in January 2025, 2025. URL: https://www.destatis.de/DE/Presse/Pressemitteilungen/2025/02/PD25_077_132.html, accessed on July 14, 2025.
- [3] Finkel P.; Wurster P.: Unlocking Tacit Knowledge in Industrial Production: Exploring Barriers, Practices, and LLM-Driven Potentials for Knowledge Management [Just Accepted]. In: Proceed. of the 59th Hawaii Int. Conf. on Sys. Sc. (HICSS) (2026).
- [4] Ackoff., R. L.: From Data to Wisdom. In: Journal of Applied Systems Analysis (1989) 16, pp. 3–9.
- [5] Alavi, M.; Leidner, D. E.: Review: knowledge management and knowledge management systems: conceptual foundations and research issues. In: MIS Quarterly 25 (2001) 1, pp. 107–36. DOI: <https://doi.org/10.2307/3250961>.
- [6] Fenoglio, E.; Kazim, E.; Latapie, H.; Koshiyama, A.: (2022). Tacit knowledge elicitation process for industry 4.0. In: Discover Artificial Intelligence (2022), 2(1), 6.
- [7] Schiedermaier, I.; Kick, E.; Baumgartner, M.; Kopp, T.; Kinkel, S.: Knowledge management in SMEs: Criteria for identifying key internal personnel. In: Journal of Economic Factory Operation 118 (2023) 6, pp. 395–399. DOI: <https://doi.org/10.1515/zwf-2023-1087>.
- [8] Rowley, J.: The wisdom hierarchy: representations of the DIKW hierarchy. In: Journal of Information Science 33 (2007) 2, pp. 163–180. DOI: <https://doi.org/10.1177/0165551506070706>.
- [9] Bostrom, R. P.; Heinen, J. S.: MIS problems and failures: a socio-technical perspective. In: MIS Quarterly 1 (1977) 3, pp. 17–32.
- [10] Rüllicke, S.: Process-integrated knowledge management – a solution to demographic change. In: Mehlich, P.; Brandenburg, T.; Thielsch, M. (ed): Business Psychology in Practice – Topics and Case Studies for Study and Application. Münster 2014, pp. 249–263.
- [11] Sumbal, M. S.; Tsui, E.; Durst, S.; Shujahat, M.; Irfan, I.; Ali, S. M.: A framework to retain the knowledge of departing knowledge workers in the manufacturing industry. In: VINE Journal of Information and Knowledge Management Systems 50 (2020) 4, pp. 631–651.
- [12] Hoerner, L.; Schamberger, M.; Bodendorf, F.: Using tacit expert knowledge to support shop-floor operators through a knowledge-based assistance system. In: Computer Supported Cooperative Work (CSCW) 32 (2023) 1, pp. 55–91.
- [13] Shadbolt, N. R.; Smart, P. R.; Wilson, J.; Sharples, S.: Knowledge elicitation. In: Evaluation of human work (2015), pp. 163–200.
- [14] Finkel, P.; Wurster, P.: Analysis of the Current State and Best Practices of Knowledge Management Applications in the Manufacturing Industry [Just Accepted]. In: Proceed. of the 19th International Conference Interdisciplinarity in Engineering (2026).
- [15] Schönfeld, D.: Application examples for AI in industrial service. In: Altenfelder, K.; Kieffer-Radwan, S.; Schönfeld, D. (ed): Services Management and Artificial Intelligence. Wiesbaden 2025. DOI: https://doi.org/10.1007/978-3-658-46665-7_2.
- [16] Zur Heiden, P.; Kaltenpoth, S.: Knowledge management for maintenance and repair in distribution networks – Design of an assistance system based on a large language model. In: HMD Praxis der Wirtschaftsinformatik 61 (2024), pp. 911–926. DOI: <https://doi.org/10.1365/s40702-024-01074-3>.
- [17] Storey, V. C.: Knowledge Management in a World of Generative AI: Impact and Implications [Just Accepted]. In: ACM Transactions on Management Information Systems (2025). DOI: <https://doi.org/10.1145/3719209>.
- [18] O'Leary, D. E.: Large Language Models and the Rebirth of Enterprise Knowledge Management. In: IEEE Computer 57 (2024) 9, pp. 20–24.
- [19] Hadi, M. U.; Tashi, Q. A.; Qureshi, R.; Shah, A.; Muneer, A.; Irfan, M.; Zafar, A.; Shaikh, M. B.; Akhtar, N.; Wu, J.; Mirjalili, S.: Large Language Models: A Comprehensive Survey of its Applications, Challenges, Limitations, and Future Prospects (2023).
- [20] Balzer, V.: Strategic Planning of Production Competencies. University of Stuttgart 2024. <http://dx.doi.org/10.18419/opus-15010>.
- [21] Van den Bent, S.; Pernisch, R.; Schlobach, S.: Investigating Knowledge Elicitation Automation with Large Language Models [Under Review]. In: Semantic Web Journal (2025).
- [22] Dengel, A.: Knowledge Representation. In: Semantic Technologies. Heidelberg 2012, pp. 21–72.

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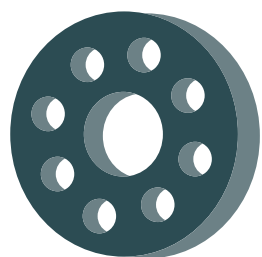
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Keywords

work design, digitally transformed work, work design criteria, learning organization, learning support



Prof. Peter Dehnbostel is involved in research and teaching at TU Dortmund and also teaches courses in part-time master's programs at various universities on topics related to continuing vocational training and corporate education management.

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New forms of learning organization and support

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Work design that promotes learning and competence development is essential for new work and organizational concepts such as “learning organizations” and “Industry 4.0”. Developing and applying criteria for promoting learning and competence development in the design of digitally transformed work enables more effective and efficient work processes, makes work more human-centered, and aligns with the AI-based future of work. Digitalization also includes work-integrated forms of learning such as online communities, learning platforms, and digital cognitive assistance systems. In the future, work design that promotes learning and competence development will be a central task of corporate training and personnel and organizational development.

The use of digital technologies is fundamentally changing work. This article first describes digitally transformed work before explaining the related criteria for learning- and competence-promoting work design.

Work design is generally defined as the creation of work systems in alignment with technical, ergonomic, and economic research, as well as the optimal interaction between employees, work equipment, work methods, and workplaces [1, 2]. Key areas include anthropometric, physiological, and safety-related work design. Another area is learning- and competence-promoting work design, which aims to support and improve learning and competence development at work [3].

Work design, which was initially classified as merely conducive to learning, has been the subject of theory and practice since the 1980s. Primarily an ergonomics subject at first, it later became important for occupational and organizational psychology, management and business administration, and vocational and continuing education. Historically, optimization criteria for work design have been considered crucial since it became clear that the workplace must be distinguished from the rest of life in terms of space, time, and organization. Measures and methods for work design have existed for centuries, even if they were not always understood or referred to as such. This is demonstrated, for example, by the apprenticeship system and master craftsman qualifications in the Middle Ages.

Work design that promotes learning and competence development is beneficial for both companies and employees. It enables companies to achieve greater effectiveness and efficiency in their work processes. Work that is designed to promote learning and competence development has become an important economic factor for companies in terms of their competitiveness within national and international markets. For employees, on the other hand, professional skills and career paths depend largely on at-work learning. Work must therefore be designed accordingly.

Digitally transformed work

Since the 1970s, changes in the world of work have been reflected in restructured organizational concepts and the onset of digitalization. This refers to the conversion of analog data into digital data and the resulting use of digital technologies. Workplaces have turned from digitalization focused primarily on technical processes to comprehensive digital transformation, characterized by the rapid spread of digital technologies, the subjectification of work, changed interactions, work-integrated learning, and the creation of innovative forms of learning.

In connection with the digital transformation of work, the introduction and spread of key digital technologies are bringing work-integrated learning and the subjectification of work to the fore. The latter manifests itself in two ways: on the one hand, companies demand subjective performance and behavioral dispositions such as flexibility and self-management; on the other hand, employees bring subjective demands to work, such as the desire to perform independent and meaningful tasks [4]. The subjectification of work not only changes individual work behavior but also affects the cooperation and interaction of employees. This is particularly evident in collaboration and in changed human-machine interactions, which are redefining the position of humans in work, especially with regard to generative AI [5].

Learning at work, as the oldest and most widespread form of professional qualification, has experienced a renaissance with the advent of digitalization. The goals, content, forms, and methods of learning at work are undergoing profound change. Advancing digitalization is particularly strengthening informal learning and shaping the reflective nature of operational work. As a result,

	Criterion	Brief description
1	Digitalization	Conversion of analog data and information into digital formats and the resulting use of digital technologies, including for work-related changes.
2	Project orientation/holistic approach	Coherent task processing based on reflective professional competence.
3	Subjectification/scope for action	Strengthening normative subjectivity and associated self-directed, competence-based action.
4	Experience of problems and complexity	Internal and external experiences in digitalized work under the special qualification requirements of the VUCA world and agility.
5	Social support/interaction	Social relationships, communication, collaboration, human-machine interaction.
6	Individual development/educational relevance	Acquisition and development of comprehensive professional skills; educational orientation through subject-centered work awareness, experiential knowledge, and expanded professionalism.
7	Professionalization	Increased expertise and knowledge through successful action strategies, digital networking, and formal and informal continuing education.
8	Reflexivity	Opportunities for structural and self-reflexivity; reflexivity as conscious, critical, and responsible evaluation of actions.

Figure 1: Criteria for work design that promotes learning and competence.

work-integrated learning is becoming a constitutive part of work. Although this work-integrated learning, as a necessary requirement of digital work, is dominated by informal learning, it also includes organized learning. It can thus be divided into purely informal learning and learning that combines informal, non-formal, and formal learning processes [6, 7].

Criteria for work design

The last few decades have seen the interdisciplinary development of practical principles, characteristics, and criteria for work design that promotes learning. These must, however, be updated with regard to the future of work, especially AI-related developments. Based on the current state of research, eight criteria can be summarized that all contribute to learning- and competence- promoting work design.

These criteria, which are explained in the specialist literature [3, 8], place self-directed learning of individual employees and groups at the center of competence development. By expanding from a work design that promotes learning to one that promotes learning and competence, holism, competence-related subjectivity, and competence development through work-integrated learning are incorporated into the design. The main value of such work design lies in the fact that learning is used

to increase productivity. This makes learning work-oriented and structured and promotes the acquisition of professional skills as part of comprehensive professional competence.

The practical and design-related application of the criteria depends largely on company-related factors such as industry affiliation, company size, work and organizational concepts, and corporate culture. They can thus be implemented through negotiation. They are not considered quality criteria per se, because whether they have a promoting or inhibiting effect on learning also depends on individual characteristics such as the individual's level of development, attitudes, and learning history. For example, a large scope for action may promote learning for one person but inhibit learning for another. The question of whether work promotes learning and competence is therefore not only subject to objective criteria but must always be viewed in relation to the dispositions of the individuals involved.

Work-integrated forms of learning support

The forms of learning support described in the following section contribute significantly to work design. Both learning forms combine work and learning, largely meet the criteria for work that promotes learning and

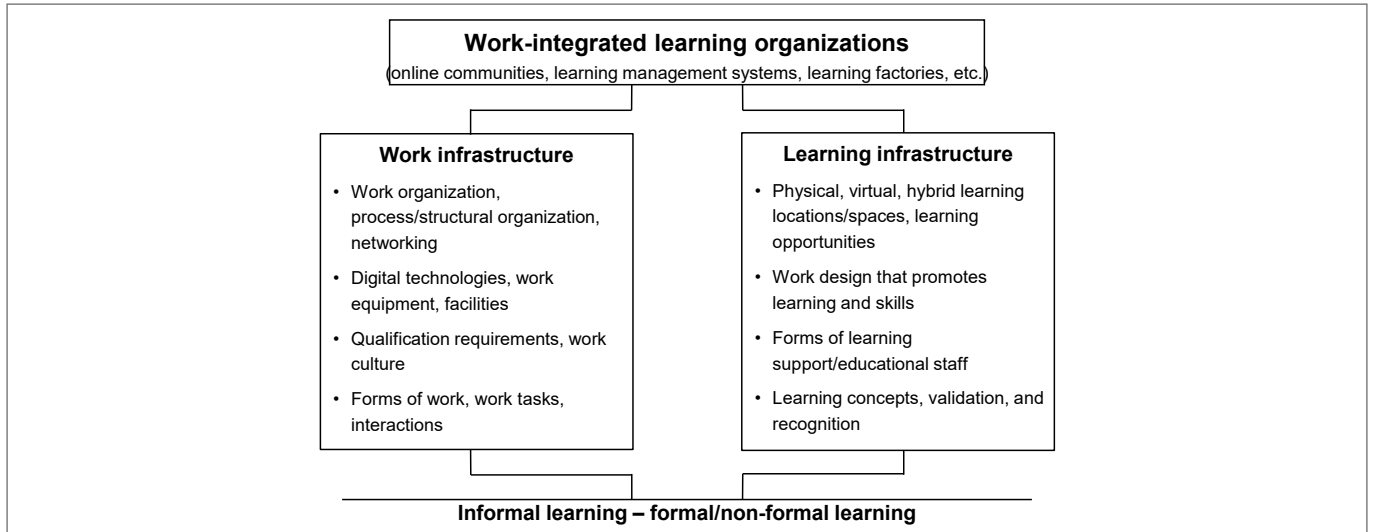


Figure 2: Dual infrastructure of work-integrated learning organization forms.

competence, and promote the qualification and competence development of employees. While learning support constitutes an independent branch supplemental to work infrastructure, some forms can be integrated directly into existing work processes. They enrich these processes by providing human and technological resources that support learning during work activities.

Both forms of learning explored here were only introduced in significant numbers with the emergence of digitalization in the 1980s/1990s [3]. As forms that organize and support learning at work, they have become necessary to keep up with the growing complexity and uncertainty of the modern world of work and careers. In conventional industrial work, with its fixed and thoroughly planned work structures, there was no need for such forms of learning in view of the hierarchically structured organizational, process, and management structures. Today's work structures and processes are becoming increasingly complex, borderless, and agile; they thus require these forms of learning.

Learning islands, learning centers, communities of practice (CoP), and work and learning tasks are now considered classic forms of learning organization. The learning center established at BMW AG in 1985 serves as a model for organizational development [9]. Newer, digitally oriented forms of learning organization include online communities, learning management systems (LMS), learning experience platforms (LXP), and learning factories in the workplace.

Learning organization is aimed both at the qualification requirements of work and at the individual and group-related competence development of employees. It thus takes into account individual experiences and subjective interests while at the same time meeting the learning and innovation requirements of companies. As **Figure 2** shows,

work infrastructure and learning infrastructure are intertwined. This dual infrastructure expands work-integrated learning and combines informal learning with non-formal and formal learning. Or, to put it another way, workplaces and work processes are supplemented by organized learning from a learning systems and competence theory perspective without being formalized and thus losing their characteristic features.

Work-integrated learning support forms

Work-integrated forms of learning usually represent long-term assistance and support in the workplace, which often also includes advisory functions. They are directly aimed at promoting and further developing learning and competence processes in individuals and groups. In doing so, they shape work in a way that promotes learning and competence, strengthens experiential knowledge, and contributes to the preservation of career-related insights.

The focus of learning support is on informal learning, which is linked to non-formal and formal learning and is reflected in different personnel compositions. Until now, this has primarily taken place in the context of vocational training measures in the workplace and, beyond that, in part-time and dual study programs. With the ongoing digitalization of work, digital assistance systems have also emerged that support work activities in the context of human-machine interaction.

As shown in **Figure 3**, learning support in the workplace takes four primary forms, which are characterized by the following features: digital assistance systems, coaching, mentoring, and learning process support [3].

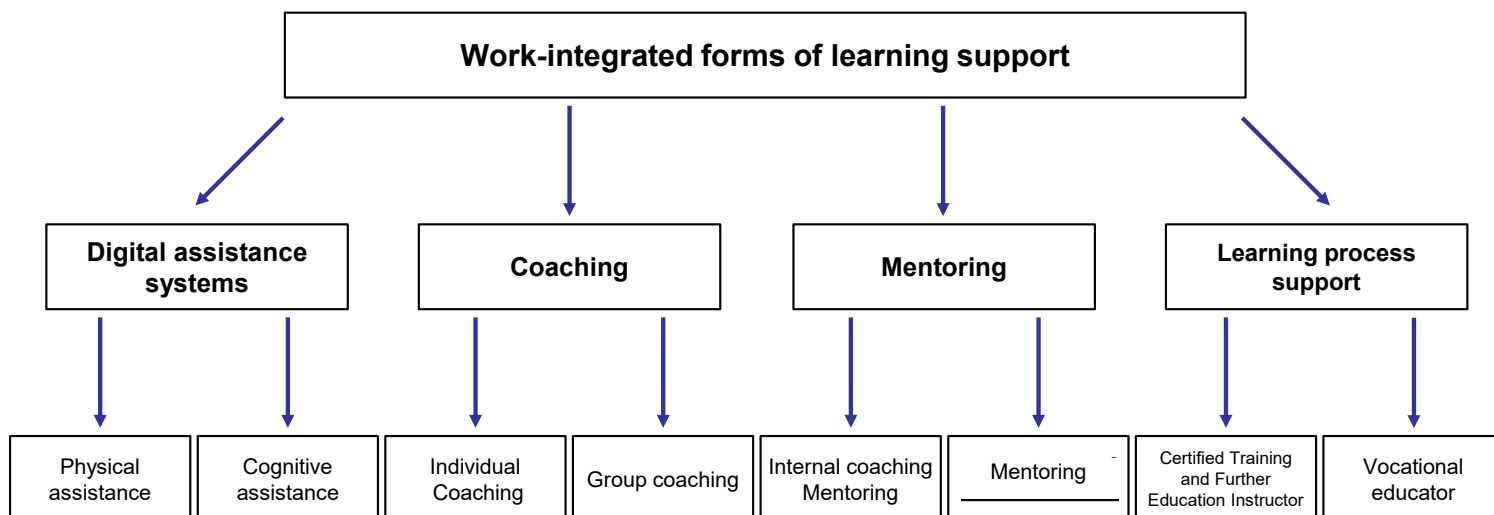


Figure 3: Forms of work-integrated learning support.

Digital assistance systems are a result of the digitalization of work and are based on digital technologies [7, 10, 11]. A distinction must be made between cognitive and physical assistance. The latter contributes to ergonomic work design and was already widely used in the early days of digitalization, particularly in the first generation of robots in the automotive industry [12]. Digital cognitive assistance supports work activities and contributes to problem-solving and decision-making. It promotes informal as well as organized learning. Well-known examples include immersive technologies such as virtual, augmented, and mixed reality (VR/AR/MR) as well as worker assistance systems.

Coaching is by far the most widespread form of support in the working world. It enables individuals and groups to reflect and further develop their learning and competence development processes in a professional environment [3]. This increases independence and self-management and expands competence. Helping people to help themselves is a guiding principle of coaching. The coach is an expert in support and counseling as well as an expert in the process. Different forms of coaching take place in companies, such as individual, team, and project coaching, as well as collegial coaching. With the advance of digitalization, online or e-coaching is becoming increasingly important.

Mentoring is a form of workplace support in which an experienced person—the mentor—supports a person seeking to gain qualifications, the mentee, in a direct one-to-one interaction [3]. It is a traditional form of support that is being expanded and reinforced via digitally transformed work. It serves to support and promote the professional development of young high-potential employees. A distinction is made between internal and

external mentoring, as well as between formal and informal mentoring. Mentoring is increasingly taking place via digital media and in the form of blended learning concepts. It is divided into different variants such as cross-mentoring and e-mentoring. Peer mentoring has also emerged in digital work, where employees exchange ideas and support each other directly in the work process. Peer mentoring is sometimes classified as informal mentoring.

Learning process support refers to support provided in the workplace as part of a qualification program [3]. This may involve training or further education, adaptation training, or other professional development. Learning process support is understood as direct personal support for employees and is carried out by trained learning process support staff or by training and further education instructors. It is also part of the recognized, broadly based advanced training professions of “Certified Training and Further Education Instructor” and “Certified Vocational Instructor” [13].

Future prospects for learning- and competence-promoting work design

Digitally transformed work is an expression of profound changes in the world of work and, in an epochal comparison of industrial revolutions, is still in its infancy. Already today, 60-80% of the professional competence of skilled workers is acquired informally and supplemented by non-formal and formal skills acquired at work. Work design that promotes learning and competence is a key factor in enabling and guiding this competence development. It is therefore important to systematically anchor and

professionalize this task in corporate training and personnel and organizational development.

Key tasks include the active application and implementation of the above criteria and the constructive organization of work, taking into account human resources, work efficiency, and vocational training requirements. At the same time, the expansion of learning organization and learning support forms must be promoted, with the ongoing digital transformation acting as a key driver. This is reflected, among other things, in the increasing spread of learning management systems and learning experience platforms in an increasingly platform-based working world. Finally, the recognition and validation of skills acquired through work-integrated learning are essential. In addition to recognition by companies, this requires national regulations and a comprehensive validation system, as has already been successfully established in several European countries, such as Switzerland and Austria.

Bibliography

- [1] Brödner, P., Knuth, M. (eds.): Nachhaltige Arbeitsgestaltung. Trendreports zur Entwicklung und Nutzung von Humanressourcen. Munich Mering 2002.
- [2] Landau, K.: Lexicon of Work Design. Best Practice im Arbeitsprozess. Stuttgart 2007.
- [3] Dehnbostel, P.: Betriebliche Bildungsarbeit. Kompetenzbasierte Berufs- und Weiterbildung in digitalen Zeiten. 3rd edition. Baltmannsweiler 2022.
- [4] Kleemann, F. et al.: Subjektivierung von Arbeit – Ein Überblick zum Stand der Diskussion. In: Moldaschl M.; Voß, G. G. (eds.): Subjektivierung von Arbeit. 2nd edition. Munich 2023, pp. 57-114.
- [5] Butollo, F. et al.: Die Symbiose von generativer KI und Arbeit: Erweiterung der Horizonte oder Erosion menschlicher Kompetenz? Weizenbaum Discussion Paper #41, 2024. URL: https://www.weizenbaum-institut.en/media/Publikationen/Weizenbaum_Discussion_Paper/Weizenbaum_Discussion_Paper_41.pdf, accessed 24.08.2025.
- [6] Dehnbostel, P.: Informelles Lernen in der Industrie 4.0. Betriebliche Bildung in informellen, nichtformalen und formalen Kontexten. In: Industry 4.0 Management 32 (2016) 3, pp. 23-26.
- [7] Warnhoff, K.: Arbeitsintegriertes Lernen in der Industrie 4.0. Eine qualitative Analyse verschiedener Assistenzsysteme in der Montage. In: Industry 4.0 Science 41 (2025) 2, pp. 20-29.
- [8] Dehnbostel, P.: Lern- und kompetenzförderliche Arbeitsgestaltung in der digitalisierten Arbeitswelt. In: ARBEIT 27 (2018) 4, pp. 269-294.
- [9] Markert, W.: Die LERNSTATT. Ein Modell zur beruflichen Qualifizierung von Ausländern am Beispiel der BMW AG. Vom Sprachmodell für Ausländer zum betrieblichen Organisationsentwicklungsmodell. Berlin; Bonn 1985.
- [10] Mattik, B.; Kretschmer, V.: Digitale Assistenzsysteme in der Logistik. Whitepaper Fraunhofer IML. Dortmund 2021. URL: <https://publica.fraunhofer.de/entities/publication/29577cb4-e6a6-4fa4-ba52-bb2b79fa26aa>, accessed 24.08.2025.
- [11] Land, M. et al.: Virtuelle Assistenzsysteme für ein kompetenzorientiertes Lernen in überbetrieblichen Berufsbildungsstätten. In: Dehnbostel, P. et al. (eds.): Kompetenzentwicklung in der digitalen Arbeitswelt. Stuttgart 2021, pp. 237-250.
- [12] Jürgens, U. (2023): Automatisierung und Arbeit in der Automobilindustrie. Von Henry Ford zur Industrie 4.0. Baden-Baden 2023.
- [13] Dehnbostel, P.: Perspektiven des betrieblichen Bildungspersonals unter besonderer Berücksichtigung aus- und weiterbildender Fachkräfte. In: Grundlagen der Weiterbildung Praxishilfen (GdWH), Contribution No. 7.60.410, Cologne 2023, pp. 1-23.

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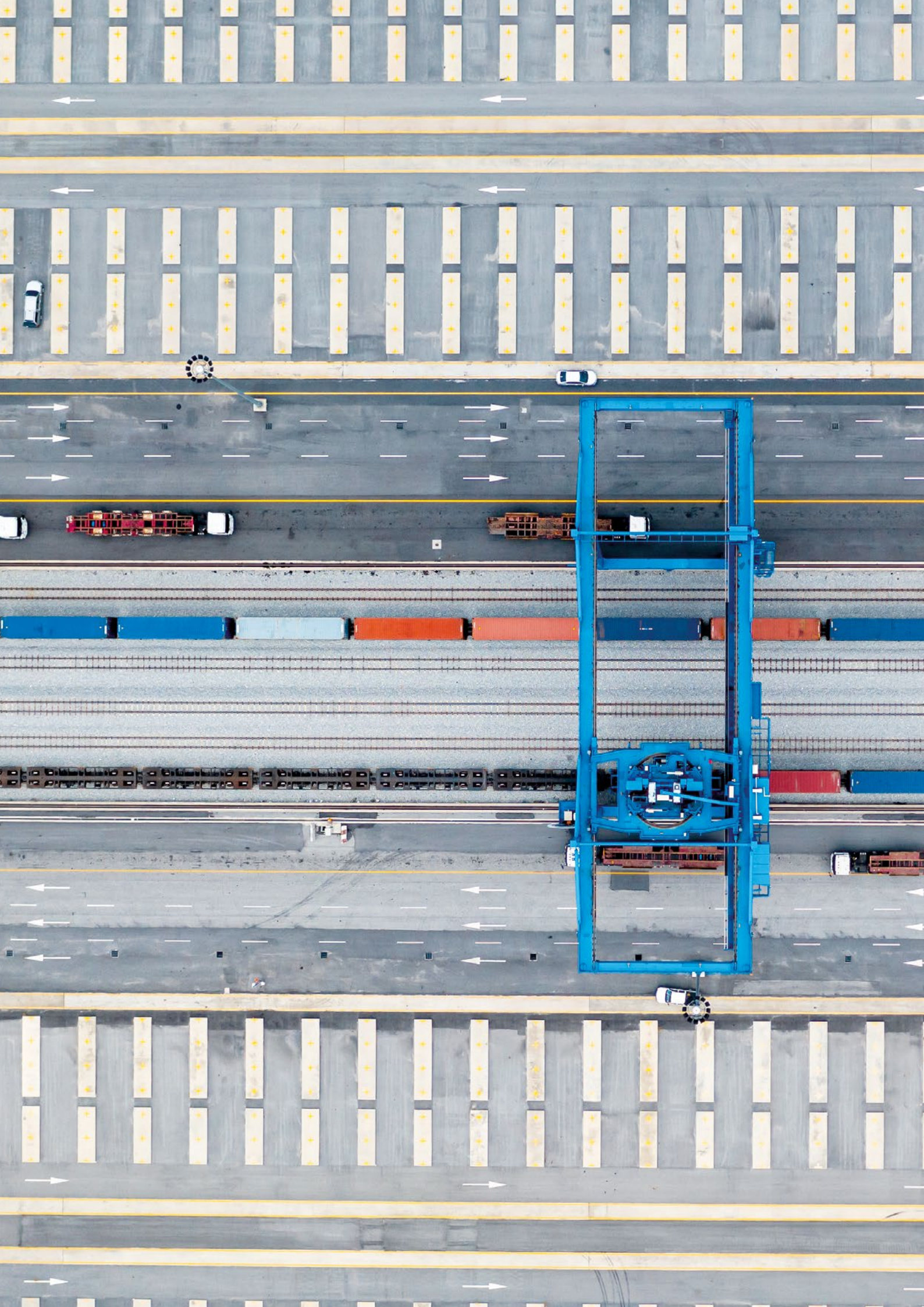
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Electric Trucks in Intermodal Terminal Pre- and Post-Carriage

Electric trucks (e-trucks) are considered a promising solution for more climate-friendly logistics. They can reduce emissions in pre- and post-transport, especially in combined transport (CT). But how well can e-trucks actually be integrated into the operation of CT terminals? What challenges exist in terms of planning, charging infrastructure, and energy supply? Scientific studies, current industry reports, and an interview provide insight.

Keywords

combined transport, electric trucks, transshipment terminals, charging infrastructure, CO₂ reduction, sustainable logistics



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Electric Trucks in Intermodal Terminal Pre- and Post-Carriage

Impact on terminal processes in combined road-rail freight transport

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Electric trucks (e-trucks) play an important role in reducing CO₂ emissions especially on short distances in pre and post-carriage in combined road-rail freight transport (CT). Using the example of a CT terminal, this article highlights the logistical and energy challenges involved in using e-trucks to establish suitable charging infrastructures and ensuring a reliable power supply.

Freight transport in Germany has experienced steady and strong growth in recent decades [1]. Despite the use of various modes of transport, road freight transport remains the dominant form of transport to this day [2]. Within rail freight transport, however, combined transport (CT) is showing above-average, dynamic growth. Forecasts up to 2026 assume continued double-digit growth rates, which underlines the increasing importance of CT as an environment- friendly alternative in the freight transport sector [3].

In 2022, pre and post-carriage in CT [4] accounted for 15% of road transport (303.9 million kilometres in total) in Germany. This illustrates the key role of road transport as a link within intermodal transport chains. At the same time, absolute CO₂ emissions from road freight transport rose by around 14.6% between 1995 and 2023, demonstrating the ongoing influence of increasing transport volumes [5].

Electric trucks: A means of reducing CO₂ emissions in freight transport

This raises the question of how emissions from road freight transport can be reduced sustainably. One promising answer is the use of electric trucks (e-trucks) [6], which can make a significant contribution to the decarbonization of freight transport [7].

The need to reduce emissions arises not only for environmental reasons, but also from clear political and social demands (Fig. 1).

According to a forecast by strategy consultancy Strategy&, around 91% of all new truck registrations in Europe will be electric by 2040. A similarly high proportion of around 90% is expected in North America and China [8]. **Figure 1** shows the projected development of the share of electric trucks in total sales in these three regions between 2020 and 2040. The graph illustrates the global trend toward the electrification of heavy-duty transport. At the same

time, this also requires the expansion of the charging infrastructure, such as at transshipment terminals in combined road-rail freight transport (CT). According to the Federal Office for

Logistics and Mobility (BALM), CT refers to the transport of goods in a loading unit. Most of the route is covered by rail, inland waterways or seafaring vessels and the pre- and post-carriage by road [14]. CGT terminals, as hubs in CGT, face the challenge of efficiently managing both the charging requirements of electric trucks and the power needs of other consumers, such as cranes and conveyor systems.

This article aims to analyze the status of the use of electric trucks in intermodal transport, both from the perspective of scientific research and based on current reporting in the trade press. To address the gap between theoretical potential and practical implementation, a three-step approach is taken: First, it examines the state of research on potential and obstacles. These findings are then reflected in reports from operational practice. Finally, an expert interview with a large, combined transport terminal operator validates the analysis with practical insights and confirms the challenges identified.

State of research on the use of electric trucks in combined transport

CT is an integral part of modern logistics networks in both Germany and Europe. Although trucks remain the most important means of transport, more environment friendly alternatives such as freight trains and inland waterway vessels are increasingly being used on longer distances. These modes of transport have steadily increased their share of total transport volume in recent years and are considered an important part of sustainable logistics [15]. [16] shows that even today, some of the pre and post-carriage transport in combined transport (CT) could be shifted to battery-electric trucks, which would lead to annual CO₂ savings of around 13,000 tons at one CT terminal examined. If this potential were applied to all European CT terminals, it would result in potential savings of several million tons of CO₂ per year.

Pre and post-transport in combined transport is considered a particularly promising area for the early

Category	Lever/measure	Goal/qualitative effect
Political	CO ₂ differentiation of the truck toll [9]	Direct cost benefit for zero-emission trucks (e.g., toll exemption) [9]
	Vehicles with a technically permissible maximum mass exceeding 3.5 tons are subject to tolls [9]	
	Toll exemption until December 31, 2025 for zero-emission heavy-duty vehicles [9]	Promoting the roll-out of climate-friendly vehicles [9]
	Permanent exemption for zero-emission vehicles up to 4.25 tons [9]	
	Tax exemption for zero-emission vehicles [10]	Zero-emission vehicles are exempt from tax. Tax relief lowers ongoing costs and promotes dissemination [10]
Economic/financial	Purchase rebate/support programs (e.g., KsNI) until 2024 [11]	Reduction of high acquisition costs and removal of barriers to investment [11]
	Promoting charging infrastructure [12]	Financial support for the installation of (non-)public charging points [12]
Societal	Specialists and apprenticeship [13]	Adaptation of job profiles (e.g., dispatchers, workshop personnel) to e-mobility [13]

Figure 1: Overview of government and social levers for CO₂ reduction and promotion of e-trucks in freight transport.

introduction of electric trucks, as the transport distances by road are short compared to the main, rail-based leg and there are several round trips between the terminal and loading points. In addition, (in principle) charging times during the waiting, loading, and unloading processes at the CT terminal could be used without negatively impacting the productivity of the electric trucks. However, technological challenges remain, such as limited range, restricted payload, and long charging times, for which efficient solutions must be developed before the widespread use of electric trucks can be realized [6]. In particular, the insufficiently developed charging infrastructure currently poses a major challenge for the use of electric trucks [17]. The development of a high-performance charging infrastructure requires considerable investment and lengthy approval processes. The low availability of public charging points is also a limiting factor [18]. Studies show that government support programs, in particular subsidies for developing charging points, can lead to a significant increase in the introduction of electric trucks [19]. When it comes to the electrification of trucks, worse-before-better effect can be expected: the transition will initially lead to higher costs but will offer cost advantages in the long run. Despite higher

acquisition costs, electric trucks are expected to achieve a cost advantage over their lifetime, primarily due to significantly lower variable operating costs for energy and maintenance [20].

According to [21] and [22], the costs for battery-electric trucks will decline significantly because of falling battery prices and increasing energy efficiency. In this case, the break-even point will be reached faster. Therefore, initial disadvantages due to higher acquisition costs and charging times will by then only be offset by the positive effects of falling battery prices and lower operating costs. Starting in 2030, electric trucks could compete economically with diesel trucks, provided that the charging infrastructure and power grids are expanded in time.

On the other hand, targeted policy measures, such as higher permissible gross weights for electric trucks or the rapid expansion of the charging infrastructure, could significantly increase the potential for electrification [18]. In addition, the possibility of local electricity generation at industrial sites could be considered to cover part of the energy requirements of electric truck fleets [16]. **Figure 3** summarizes measures for the

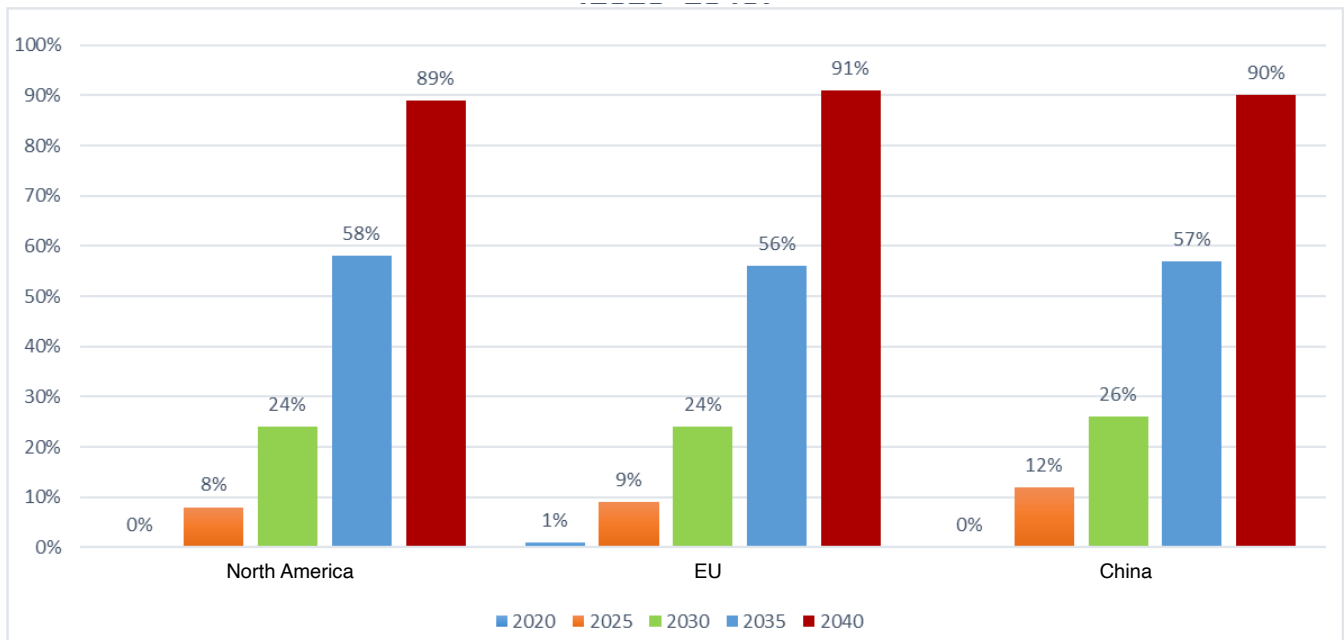


Figure 2: Forecast share of electric trucks in total sales by region (2020–2040) [8].

integration of electric trucks in combined transport and evaluates them according to their impact (electrification) and feasibility.

Research shows that the use of electric trucks in combined transport can already be beneficial assuming that suitable conditions are in place. At the same time, range and payload limits must be considered in scheduling to ensure robustness even in the event of disruptions. In addition, terminal-wide energy management and standardized data and interfaces between electric trucks, charging points, and terminal IT are coming into focus to avoid peak loads and support operational decisions.

Building thereon, the focus is now on practical application: What usage patterns, savings, and organizational solutions do real projects show—and where are the current limitations? The following section draws on current press and industry reports as well as company announcements to critically reflect on the “theoretical” potential applications of electric trucks in combined transport. This allows us to move from the theoretical “might work” to the operational “definitely works under these conditions.”

State of operational practice on using electric trucks in combined transport

In addition to scientific literature, press releases, industry reports, and company publications provide insight into the potential applications of electric trucks in combined transport. While research publications often analyze

technical potential and challenges, practical reports focus more on specific use cases, savings achieved, and organizational solutions. [23] argues that pre- and post-carriage should be gradually converted from conventional trucks to electric trucks. The electricity required might come from the company’s own photovoltaic systems. It is also apparent that terminal operators, combined transport operators, and freight forwarders are analyzing the use of electric trucks in combined transport: According to the Contargo company, for example, the use of electric trucks in combined transport on the Mannheim-Rotterdam route can slash CO₂ emissions by up to 94% compared to using only diesel trucks in road transport [24].

Parallel to technological advances, digital brokerage and organization services are becoming established that increase efficiency in combined transport. Platforms such as Rail-Flow improve coordination between operators, terminals, and freight forwarders to enable the transport of more goods by combined transport [25, 26] and could play an important role in the future in scheduling loading windows for electric trucks.

In addition, the expansion of the charging infrastructure is gaining momentum. According to [27], around 1,800 high-performance fast charging points are to be installed in 354 public places by 2030 to enable the fast charging of e-trucks during the driver’s rest periods. An additional temporary 2,400 charging points are planned. This should cover a large part of the charging demand in future and almost the entire road network. [28] documents the successful integration of electric trucks into time-critical shuttle services. After a test phase,

No.	Measure	Effect	Feasibility
1	Building charging infrastructure [17]	high	medium
2	Integrate loading into transshipment process [6]	high	medium
3	Reliable charging windows at the terminal [6]	high	medium
4	Local power generation [16]	medium	low
5	Increase in permissible gross vehicle weights for electric trucks [18]	medium	medium
6	Cost reduction due to falling battery prices [21, 20]	high	medium
7	Support programs and subsidies [19, 12]	high	high

Figure 3: Qualitative impact portfolio of key measures for integrating electric trucks into combined transport.

daily round trips could be reliably implemented, even with increased energy requirements in winter. Partnerships between freight forwarders and electric truck manufacturers also aim to increase the use of electric trucks and thus gradually increase the share of zero-emission transport [29]. Summarily, the report makes it clear that the use of electric trucks in combined transport can gradually develop from the pilot phase to application maturity.

The potential applications described above are critically examined in the following section based on an interview to validate these practical reports and gain more detailed insights into the operational challenges at the terminal. The interview was conducted online in July 2025 and then transcribed and evaluated.

Logistical requirements for operating electric trucks at intermodal terminals

The interview with a major terminal operator confirms that reducing CO₂ emissions is a key motive for introducing electric trucks in pre and post-carriage. Electric trucks are mainly used for short distances between 40 and 70 km, which is highly compatible with the range of modern models (345–400 km per charge). According to the interviewee, the existing approval for transporting-dangerous goods with electric trucks further expands the range of possible applications. Despite these possibilities, the switch to electric trucks also entails restrictions. The interview showed that route planning must be adapted to the limited range of electric trucks, with journeys over 150 km being particularly problematic, especially if there are unforeseen delays along the way. The payload is also limited. Although combined transport vehicles can have a total weight of up to 44 tons, in practice, electric trucks frequently have significantly reduced payloads to avoid compromising their range

excessively. That increases the complexity of planning and reduces flexibility compared to conventional diesel trucks. According to the interviewee, the necessary charging infrastructure also poses a major challenge, as the connection to the power grid in particular leads to high costs and requires considerable planning effort. One reason for this is that separate transformer stations are required for the power supply, which can involve lengthy approval processes. At the same time, other large energy consumers such as cranes and refrigerated containers must also be supplied at the CT terminal. To avoid peak loads and ensure power availability, an energy management system for intermodal terminals that continuously monitors power consumption and can specifically control when certain consumers are prioritized or reduced appears to be appropriate.

Outlook and existing challenges for the use of electric trucks

This article highlights the opportunities, but also the challenges to , using electric trucks in combined transport, especially at transshipment terminals. The literature reviewed and the interview conducted reveal four key challenges for the use of electric trucks in the pre and post-carriage stages of combined transport.

1. Data for transport planning: Comparable key figures on energy consumption, loading windows, dwell times, and transshipment times form an essential basis for transport planning for electric trucks in pre and post-carriage with the interface to the intermodal terminal. Currently, this data for transport planning is not yet available in a systematic, standardized form. Without this data basis, it is difficult to reliably incorporate ranges, loading requirements, and handling processes into operational transport planning.

2. Charging infrastructure at the intermodal terminal and along the transport route: The expansion of high-performance charging points extends the range of action. The challenge is that the necessary charging infrastructure is not yet available across the board and requires both investment and coordination between intermodal terminals, energy suppliers, and public operators.
3. System integration: Interfaces between fleet, terminal, and energy management, as well as advances in high-performance charging, can increase the robustness of transport planning. Different systems and a lack of standards make it difficult to exchange data consistently and prevent the efficient coordination of the energy requirements of electric trucks and terminal processes.
4. Need for political action: As shown in **Figure 1**, the success of electrification depends largely on political framework conditions. The expert interview and literature analysis confirm that market mechanisms alone cannot bear the high initial investment costs (especially for grid expansion at terminals). Clear political action is needed to accelerate approval procedures for grid expansion, investment, and power supply.

Bibliography

- [1] German Aerospace Center (DLR): Facts and figures – Freight transport in Germany. 2022. URL: https://www.dlr.de/de/aktuelles/nachrichten/2022/02/20220401_daten-und-fakten-gueterverkehr/, accessed on October 25, 2025.
- [2] Federal Office for Logistics and Mobility (BALM): Medium-term forecast for winter 2024/2025. URL: https://www.balm.bund.de/SharedDocs/Downloads/DE/Verkehrsprognose/Mittelfristprognose_Winter_2024_2025.pdf?__blob=publicationFile&v=1, accessed on October 25, 2025.
- [3] Federal Office for Logistics and Mobility: Logistics and Mobility 2025, pp. 52–58.
- [4] Federal Republic of Germany: ReMuNet Country Sheet – Germany [PDF]. 2025. URL: https://remunet-project.eu/wp-content/uploads/2025/02/ReMuNet-Country-Sheet_Germany.pdf.
- [5] Federal Environment Agency: Emissions from transport. 2025. URL: <https://www.umweltbundesamt.de/daten/verkehr/emissionen-des-verkehrs#strassenguterverkehr>, accessed on October 25, 2025.
- [6] Jahangir Samet, M.; Liimatainen, H.; van Vliet, O. P. R.; Pöllänen, M.: Road freight transport electrification potential by using battery electric trucks in Finland and Switzerland. In: *Energies* 14 (2021) 4, 823. DOI: <https://doi.org/10.3390/en14040823>.
- [7] Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection: E-trucks: Climate-friendly heavy goods transport [FAQ]. 2025. URL: <https://www.bundesumweltministerium.de/faqs/e-lkw-klimafreundlicher-schwerlastverkehr>, accessed on October 25, 2025.
- [8] Strategy&: Truck Study 2024. URL: <https://www.strategyand.pwc.com/de/en/industries/transport/truck-study.html>, accessed on October 25, 2025.
- [9] Federal Ministry of Transport: Truck toll. 2025. URL: <https://www.bmv.de/SharedDocs/DE/Artikel/StV/Strassenverkehr/lkw-maut.html>, accessed on October 25, 2025.
- [10] Energielenker Group: Building an e-fleet with electric commercial vehicles [blog post]. 2025. URL: https://www.energielenker.de/wissen/blog/elektromobilitaet/aufbau-e-flotte-mit-e-nutzfahrzeugen/?_gl=1*c8a1bf*_up*MQ..*_gs*MQ..&gclid=EAlaI-QobChMImqe0zsjCkAMV7jGDBx35fxx4EAAYBCAAEgIG3fD_BwE, accessed on October 25, 2025.
- [11] Federal Office for Logistics and Mobility (BALM): No continuation of the KsNI funding program. 2024. URL: https://www.balm.bund.de/SharedDocs/Kurzmeldungen/DE/Foerderprogramme/KsNI/KsNI_Keine_Fortfuehrung.html?nn=537792, accessed on October 25, 2025.
- [12] Hessian Ministry of Economics, Energy, Transport, Housing, and Rural Affairs: Hesse promotes charging infrastructure for heavy commercial vehicles – "Heavy Duty Charging." 2025. URL: <https://wirtschaft.hessen.de/presse/hessen-foerdert-ladeinfrastruktur-fuer-schwere-nutzfahrzeuge-heavy-duty-charging>, accessed on October 25, 2025.
- [13] Fraunhofer Institute for Manufacturing Technology and Applied Materials Research (IFAM): Online seminar "Depot charging of electric trucks and buses – legally compliant and economically feasible?" 2025. URL: <https://www.qualifizierung.ifam.fraunhofer.de/de/weiterbildung-elektromobilitaet/online-seminares-elektromobilitaet/depotladen-von-e-lkw-und-e-bussen-rechtssicher-und-wirtschaftlic.html>, accessed on October 25, 2025.
- [14] Federal Office for Logistics and Mobility. (n.d.). What is combined transport and how is it carried out? [FAQ]. URL: <https://www.balm.bund.de/SharedDocs/FAQs/DE/Gueterkraftverkehr/KombinierterVerkehr.html>, accessed on 25 October 2025.
- [15] Federal Ministry of Digital and Transport (BMDV): Logistics Innovation Program 2030. 2019. URL: https://www.bmv.de/SharedDocs/DE/Anlage/G/innovationsprogramm-logistik-2030.pdf?__blob=publicationFile, accessed on October 25, 2025.
- [16] Bergqvist, R.; Monios, J.; Jönsson, J.: Potential for rapid adoption of battery-electric heavy-duty trucks for pre- and post-haulage at intermodal terminals. In: *Research in Transportation Business & Management* 50 (2023), 101035. DOI: <https://doi.org/10.1016/j.rtbm.2023.101035>.
- [17] European Automobile Manufacturers' Association (ACEA): Position paper – Heavy-duty vehicles: Charging and refueling infrastructure requirements. 2021. URL: https://www.acea.auto/files/ACEA_Position_Paper-Heavy-duty_vehicles-Charging_and_refuelling_infrastructure.pdf, accessed on October 25, 2025.
- [18] Liimatainen, H.; van Vliet, O.; Aplyn, D.: The potential of electric trucks – An international commodity-level analysis. In: *Applied Energy* 236 (2019), pp. 804–814. DOI: <https://doi.org/10.1016/j.apenergy.2018.12.017>.
- [19] Raoofi, Z.; Mahmoudi, M.; Pernestål, A.: Electric truck adoption and charging development: Policy insights from a dynamic model. In: *Transportation Research Part D: Transport and Environment* 139 (2025), 104515. DOI: <https://doi.org/10.1016/j.trd.2024.104515>.
- [20] Raoofi, Z.; Andruetto, C.; MacDonald, R.: How does electrification impact road freight transport efficiency? A system dynamics approach. SSRN. 2024. DOI: <http://dx.doi.org/10.2139/ssrn.4948350>.
- [21] Link, S.; Stephan, A.; Speth, D. et al.: Rapidly declining costs of truck batteries and fuel cells enable large-scale road freight electrification. In: *Nat Energy* 9 (2024), pp. 1032–1039. DOI: <https://doi.org/10.1038/s41560-024-01531-9>.
- [22] Fraunhofer ISI: Zero-emission trucks: Declining costs imply fast market diffusion [Press release]. 2024. URL: <https://www.isi.fraunhofer.de/en/presse/2024/presseinfo-18-emissionsfreie-lkw-sinkende-kosten.html>, accessed on October 25, 2025.

- [23] Sievert Logistik SE: By rail to and from France – Sievert Logistik SE focuses on sustainable construction material transport. 2024. URL: <https://www.sievert-logistik.de/de/aktuelles/presse/news/per-schiene-von-und-nach-frankreich-sievert-logistik-setzt-auf-nachhaltige-baustoff-transporte.html>, accessed on October 25, 2025.
- [24] Contargo: econtargo – the zero emissions way. URL: <https://www.contargo.net/de/business/econtargo-the-zero-emissions-way>
- [25] Rail-Flow GmbH: Intermodal Capacity Broker [website]. 2025. URL: <https://www.rail-flow.com/intermodal-capacity-broker-spediteure/>, accessed on October 25, 2025.
- [26] European Cargo Logistics GmbH: Digital intermodal booking portal "modility" online: ECL is a development partner [website]. 2024. URL: <https://www.ecl-online.de/en/service/ecl-aktuell/modility.html>, accessed on October 25, 2025.
- [27] Eurotransport: Fast charging network for trucks on federal highways – Federal government gives green light for public fast charging network for trucks with 4,200 charging points on highways. In: trans aktuell 13 (2024) 4. URL: https://download.eurotransport.de/downloads/trans_aktuell/2024/ta_digital_13_2024.pdf, accessed on October 25, 2025.
- [28] L.I.T. AG: L.I.T. launches fully electric freight transport in just-in-sequence operation [press release]. PresseBox. 2025. URL: <https://www.pressebox.de/pressemitteilung/lit-ag-logistik-information-transport/li-t-startet-vollelektrischen-gtertransport-im-just-in-sequence-einsatz/boxid/1245769>, accessed on October 25, 2025.
- [29] Böhm, K.: DB Schenker puts the first ten of 150 electric trucks into service. move4zero. 2025. URL: <https://www.move4zero.de/db-schenker-stellt-die-ersten-zehn-von-150-e-lkw-in-dienst-2779644>, accessed on October 25, 2025.

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Has the Time Come for an Energy Revolution in Intralogistics?

Hydrogen fuel cells are a sustainable option for industrial trucks, as they offer fast refueling, zero emissions, and consistent performance—ideal for demanding warehouse or production tasks. However, high acquisition costs and uncertainties among potential users are slowing down their introduction. Economic and operational aspects should be at the forefront when considering whether and for whom fuel cells currently make sense.

Keywords

batteries, fuel cells, hydrogen, intralogistics, material handling, forklifts, fleet management, sustainability



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Has the Time Come for an Energy Revolution in Intralogistics?

The current status of hydrogen fuel cell-powered MHE

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Hydrogen fuel cells promise to be a sustainable alternative to fossil fuel or battery-electric material handling equipment (MHE) in various production or warehouse contexts. Short refuelling times, an absence of carbon emissions, and constant power input put fuel cell-powered MHE at an advantage in high-intensity work environments. However, various barriers to the adoption of fuel cells remain, including considerations surrounding cost and efficiency. In this article, the authors review the current state of the art regarding the economic viability and operational efficiency of fuel cells. They thereby determine whether their increased use is worthwhile under current conditions and, if so, for whom.

The question of when a switch to fuel cell-powered material handling equipment (MHE; see **Figure 1** for an illustrative example) becomes a worthwhile investment is still under debate. The answer depends on a variety of factors, including hydrogen supply and infrastructure, fleet size, load profile, and operation hours (see also [1], [2]). To provide a commercially viable solution to companies with a high volume of intralogistics operations, the operational efficiency and economic viability of fuel cell systems must be guaranteed. Whether or not a fleet of hydrogen-powered MHE can rival a fleet of battery-powered ones depends on factors that are not always within the user's control.

Figure 1: Fuel cell-powered forklift next to a hydrogen dispenser.



As the proliferation of fuel cell-powered MHE continues, it is of critical importance to continue studying and evaluating its performance, especially in comparison to competing technologies such as, first and foremost, lithium-ion batteries. Several studies published over the last 15

years have evaluated or simulated the use of fuel cells against common battery-powered MHE, mostly from either an economic (e.g., return-on-investment, total cost of ownership) or operational (e.g., lifetime, range) perspective. To date, however, only few such studies have been published, despite substantial growth in the use of hydrogen for material handling applications [3] as well as a growing interest in applying hydrogen in other areas, such as for the decarbonization of heavy-duty freight transport or port areas. Below, we provide a synthesis of the most important insights from these studies.

Economic viability

Previous research in a North American context has concluded that fuel cell forklifts are not economically competitive when compared to battery-powered ones, with fast-charge forklifts being the most economically viable under high workload conditions [4]. Similarly, a total cost of ownership calculation concluded that fuel cell systems are more expensive than lead acid batteries, but not lithium-ion batteries [2]. Due to rapid advances in the development of lithium-ion batteries, however, the life cycle cost of the latter over ten years is currently estimated to be less than half the cost of proton exchange membrane fuel cells (PEMFC) or direct methanol fuel cells (DMFC) [5].

While these findings challenge the economic viability of fuel cell MHE, there is a growing body of evidence that suggests otherwise. In particular, research has shown that fuel cell forklifts can be economically competitive compared to battery systems, especially in the context of multishift operations [6]. The total cost of ownership can be reduced and the higher costs of hydrogen fuel and associated infrastructure either partially or completely offset through a reduction in labor costs associated with battery charging and swapping, as well as lower facility costs. Fuel cell

systems can also rival battery systems due to their greater life expectancy, despite higher initial costs [6].

More recent research has reached similar conclusions by demonstrating the feasibility of retrofitting a lead-acid battery-powered forklift to a hydrogen-powered one with predicted gains in the autonomy and life cycle of the forklift [7]. It has further been suggested that, for forklift users with smaller fleets (i.e., less than 50 units), which represents 80% of forklift users, direct methanol fuel cells will be even more cost-effective due to the significantly lower cost of methanol versus hydrogen infrastructure. Finally, fuel cells are particularly attractive as a replacement for diesel engine-powered forklifts because the total cost of the PEMFC forklift, hydrogen production, and the refuelling system can be recovered in less than five years [8].

Operational efficiency

One simulation suggests that fuel cell-powered material handling equipment may be particularly attractive for warehouse tasks that conform to three conditions:

- a) a medium to large fleet,
- b) high usage (i.e., three working shifts per day), and
- c) onsite hydrogen production via natural gas reforming or the use of market hydrogen [9].

Fuel cells can increase equipment uptime due to substantially shorter refuelling times compared to battery-powered MHE [10]. This does, however, depend on the efficiency of the battery swapping process, which may vary greatly [11]. According to the authors of the H2IntraDrive project report, the average refuelling time for fuel cell-powered floor vehicles is 2 minutes and 36 seconds (best case scenario), whereas the fastest battery swapping process (e-forklift with pallet truck, decentralized charging station) takes approximately 3 minutes and 20 seconds. The time-saving potential is thus only around 45 seconds. Such a scenario inevitably raises the question of whether the required investment in fuel cell infrastructure and equipment is worthwhile. In practice, however, battery swapping time has been shown to last anywhere from 3 to 25 minutes. With these more realistic estimates, time savings could be up to 92% [11].

On the other hand, fuel cell-powered floor vehicles tend to have shorter range (i.e., operating hours) compared to their battery-powered counterparts. That is, due to their higher energy capacity, the operating hours for battery-powered forklifts between charging cycles/battery swaps are almost double those of fuel cell-powered MHE [11]. Hence, despite advantages in the time required to refuel, fuel cell forklifts must refuel at least once to match the

operating time of a battery forklift. With advances in fuel cell technology, however, it is expected that the effective range will become greater over time. Moreover, due to their compactness, fuel cells benefit from lower weight compared to their battery counterparts and offer quicker startup times [12].

In terms of lifetime, fuel cells also show promise. While the average lease time for forklift trucks is around five years, fuel cells can last up to ten years or more, which is substantially longer than the lifetime of a (lead-acid) battery [10]. Based on observation data, the lifetime of fuel cells may equal that of the MHE itself, whereas MHE usually outlasts the lifetime of batteries [11]. For example, whereas a battery-powered forklift may use three batteries in its lifetime, it would only require one fuel cell.

Future outlook and research questions

Cost of hydrogen

The cost of hydrogen is a decisive factor for the adoption of hydrogen-powered MHE (**Fig. 2**). While finite fossil fuel resources such as natural gas, coal, and oil are still substantially cheaper than hydrogen for most applications, the use of fossil fuels is expected to gradually decrease, with prices increasing in the long term [13]. At the same time, the production and thus end-user costs of hydrogen will decrease substantially. Through the scale-up of hydrogen production and distribution, projections by the Hydrogen Council foresee a cost reduction by up to half for various hydrogen applications until 2030 [14]. A more conservative estimate suggests a cutting in half of the production price of hydrogen from electrolysis by 2050 [15].

In the case of material handling, fossil fuels are already in sharp decline, while the electrification of equipment has helped businesses to cut down emissions. With a decrease in hydrogen production costs, fuel cell-powered MHE will become more competitive in comparison to battery-powered (lithium-ion) MHE on top of the fact that it already provides a more sustainable alternative to common diesel and lead-acid battery-based MHE [2, 8].

Data-driven fleet management

Data-driven fleet management is becoming indispensable for effective fleet operation (see **Fig. 3** for an illustration). Investing in appropriate fleet management software not only enables close monitoring of the fleet, but also provides various options for fleet optimization, from optimizing workflows to identifying usage patterns of individual vehicles, thus guaranteeing an optimal allocation of resources.

In intralogistics operations, monitoring the usage of forklifts with sensors and appropriate fleet management software

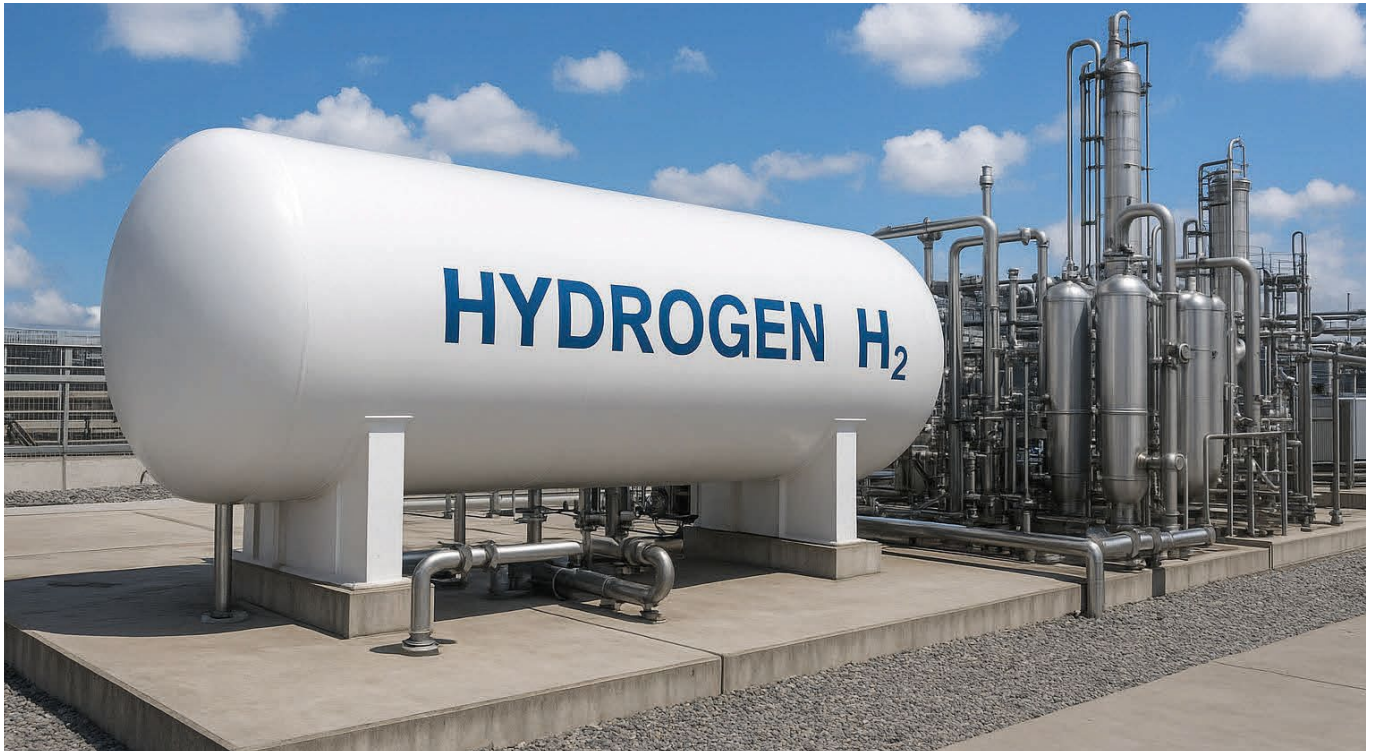


Figure 2: Example of a hydrogen storage container.

can help to optimize fuel consumption as well as helping to determine the optimal fleet size through shedding less used or unused MHE. Collecting appropriate data about the usage of MHE (e.g., hours of operation, distance travelled, charging times and workload) and relevant contextual factors (e.g. area of deployment, local temperature) is therefore crucial. For hydrogen-powered MHE, additional factors such as the tank pressure and temperature, refuelling time, and hydrogen consumption must also be considered.

Fuel cell applications beyond intralogistics

The use of hydrogen, especially green hydrogen, has great potential in intralogistics. Instead of a network of refuelling stations along a transport route, a few dispensers can suffice to power an entire fleet of MHE. The ecological argument for battery-powered devices is also guaranteed in forklift trucks through use of the intermediate battery, which is charged during operation, thus providing a constant power output. Yet, the use of hydrogen fuel cells is by no means limited to intralogistics operations. Hydrogen can have numerous applications in 1:n consumer structures due to its short refuelling times and reliable performance.

The use of hydrogen technology for shunting locomotives at freight yards, tugs in ports or pushback vehicles at airports is a good example. From a logistical point of view, it is helpful in these scenarios that one or a few hydrogen refuelling points can be made available to many devices. The high level of performance, even at the end of a work shift, makes the technology particularly interesting for

high-performance tractors. In a project that considers the use of maritime tugs or shunting locomotives, the requirements must be researched.

Other scenarios for the use of hydrogen fuel cells include the conversion of buses in public transport. The increasing density of conurbations requires lower-emission transport concepts and drive methods. The use of hydrogen in buses could be one such approach. Since the vehicles return to the depot at the end of the shift and routes and areas are already designed according to capacities and ranges, the establishment of an infrastructure with only a few refuelling points could be a viable solution.

Hydrogen now and in the future

In conclusion, while an energy revolution in intralogistics is within grasp, whether or not a switch to fuel cell-powered MHE is a worthwhile investment depends on various factors, some of which are outside the user's control. Major barriers to large-scale adoption are the cost and supply of hydrogen. Currently, fuel cell-powered MHE is only recommendable for larger fleet sizes with a high intensity workload, as the greatest economic and operational benefits can be achieved under these conditions. For smaller fleet sizes with lesser workloads, battery powered-MHE remains the preferred solution, given that the battery swapping process is more effective. However, as hydrogen is projected to become more available and affordable as a resource, it may become a viable solution for a broader range of stakeholders with more diverse workload requirements in the future.



Figure 3: Fleet management example.

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Bibliography

- [1] McConnell, V.: Fuel cells in forklifts extend commercial reach. In: Fuel Cell Bulletin 2010 (2010) 9, pp. 12-19.
- [2] Müller, M.: Fuel cell forklift systems. In: Stolten, D.; Samsun, R. C.; Garland, N. (Eds.): Fuel Cells: Data, Facts and Figures (pp. 321-333). Weinheim 2016.
- [3] Keller, A. V.; Karpukhin, K. E.; Kolbasov, A. F.; Kozlov, V. N.: Analysis of hydrogen use as an energy carrier in transport. In: IOP Conference Series: Materials Science and Engineering 1159 (2021) 1, p. 012087.
- [4] Renquist, J. V.; Dickman, B.; Bradley, T. H.: Economic comparison of fuel cell powered forklifts to battery powered forklifts. In: International Journal of Hydrogen Energy 37 (2012) 17, pp. 12054-12059.
- [5] Metzger, N.; Li, X.: Technical and economic analysis of fuel cells for forklift applications. In: ACS Omega 7 (2022) 22, pp. 18267-18275.
- [6] Ramsden, T.: Evaluation of the Total Cost of Ownership of Fuel Cell-Powered Material Handling Equipment (No. NREL/TP-5600-56408). National Renewable Energy Lab (NREL). Golden, CO (United States) 2013.
- [7] Pacheco, D. S.; Gonzalez, L. G.; Espinoza, J. L.; Campoverde, C. J.: Energy consumption of an electric forklift truck: Alternative with fuel cell and supercapacitor. In: 2019 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC), pp. 1-6.
- [8] Xiong, Z. A.; Zhou, H. et al.: Work Efficiency and Economic Efficiency of Actual Driving Test of Proton Exchange Membrane Fuel Cell Forklift. In: Molecules 27 (2022) 15, p. 4918.
- [9] Dominguez, I.; Contreras, A. et al.: Simulation of the operation of a fleet of materials handling and transport vehicles, powered by fuel cells. In: International Journal of Hydrogen Energy 40 (2015) 24, pp. 7678-7688.
- [10] Kosanić, N.; Rajković, M. et al.: Alternative energy sources for forklifts – a way to make intralogistics green. In: Proceedings of the 20th International Conference on Material Handling MHCL 2012, pp. 251-256.
- [11] Günthner, W. A.; Micheli, R.: H2IntraDrive-Einsatz einer wasserstoffbetriebenen Flurförderzeugflotte unter Produktionsbedingungen. fml-Lehrstuhl für Fördertechnik Materialfluss Logistik, Technische Universität München. URL: https://www.now-gmbh.de/wp-content/uploads/2020/09/forschungsbericht_h2intradrive_03bs112b.pdf, accessed 08.04.2025.
- [12] Qasem, N. A.; Abdulrahman, G. A.: A Recent Comprehensive Review of Fuel Cells: History, Types, and Applications. In: International Journal of Energy Research 1 (2024), p. 7271748.
- [13] Farhana, K.; Mahamude, A. S. F.; Kadrigama, K.: Comparing hydrogen fuel cost of production from various sources-a competitive analysis. In: Energy Conversion and Management 302 (2024), p. 118088.
- [14] Hydrogen Council: Path to hydrogen competitiveness: a cost perspective (2020). URL: <https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness-Full-Study-1.pdf>, accessed 19.09.2024.
- [15] Frieden, F.; Leker, J.: Future costs of hydrogen: a quantitative review. In: Sustainable Energy & Fuels 8 (2024), pp. 1806-1822.



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Loam Construction and Wooden Shelving

The logistics industry is facing fundamental change: increasing sustainability requirements and legal regulations are demanding new approaches to the construction of logistics infrastructure. Natural building materials such as clay and wood are increasingly coming into focus. A look at practical examples shows how these materials can contribute to circular construction methods and whether they are not only ecologically but also economically viable.

Keywords

sustainable logistics infrastructure, circular construction, loam construction, high rack timber warehouse, life cycle analysis, decarbonization, ecological logistics buildings, circular economy

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Loam Construction and Wooden Shelving

A contribution to sustainability in warehouse logistics

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This study examines the contribution of natural building materials, in particular loam and wood, to the sustainable development of logistics infrastructure, assessing ecological, economic, and technical dimensions across the entire life cycle. Potentials, restrictions, and supportive framework conditions are identified based on literature analyses and expert interviews. Wood proves to be technically mature and ecologically advantageous, especially in high rack construction, while loam offers high potential for energy- and resource-efficient construction. The study concludes with recommendations for research, policy, and practice to establish circular construction methods in logistics.

The logistics sector is one of the main contributors to greenhouse gas emissions in Germany. Approximately 20% of national emissions are attributable to the transport sector, of which around 35% is attributed to freight transport. Within this segment, stationary logistics processes such as storage and building operations account for around 1% of total German greenhouse gas emissions [1].

Despite this comparatively small share, the balance sheet highlights the untapped reduction potential of stationary logistics infrastructures. The construction sector as a whole accounts for around 40% of national greenhouse gas emissions [2] and the construction of logistics buildings is particularly important due to their size, design, long service life, and the considerable amount of building materials used. Life cycle-oriented planning can make a significant contribution to decarbonization in this area [3].

The aim of this study is to systematically evaluate the potential of natural building materials in logistics construction. The focus is on loam and wood as examples of resource-saving materials, whose ecological, economic, and technical suitability are assessed in the context of circular construction.

Sustainability in logistics processes

In order to cope with the increasing complexity of international supply chains, more and more large-scale logistics centers are being built, which make it possible to respond flexibly to volatile market requirements and strike a balance between transport costs and location. While progress in decarbonizing transport is primarily achieved through alternative drive technologies, choice

of transport mode, or optimization of planning and transport processes, warehouse logistics offers additional reduction potential along the entire value chain [4].

At the structural level, resource-saving construction methods and the conscious selection of environmentally friendly, renewable, or recyclable building materials offer considerable potential for both the supporting structure and the interior fittings of logistics buildings. The use of renewable energies (e.g., photovoltaics) and energy-efficient building technology to control air conditioning, lighting, and water consumption also contributes to reducing operational energy requirements [5].

Life cycle analysis of sustainable logistics infrastructures

In the technical literature, the life cycle of a building is typically divided into four phases (**Fig. 1**).

Life cycle analysis is a key approach to the ecological assessment of buildings, as it differentiates between embedded emissions, which appear primarily in phases 2 and 4, and operational emissions, in phase 3. Up to 80% of embedded emissions depend on the building materials selected, while 80 to 90% of operational emissions are predominantly determined by energy consumption during the use phase. Both values are taken from a figure on the emission structure of industrial warehouse buildings presented in source [7].

Methodology

The potential of natural building materials in the logistics industry is systematically assessed using a qualitative approach to empirical social research, consisting of structured literature research and guided expert interviews. Based on both methods, an assessment is made in which the building materials loam and wood are evaluated in



Figure 1: Life cycle phases of a building [6].

terms of their technical suitability and economic and ecological properties. The assessment serves to systematically compile and compare results from literature, research, and practice [8].

Literature review using the PRISMA method

The systematic literature review was conducted using the Google Scholar database and was based on a multi-stage selection process in accordance with the PRISMA method (Fig. 2). The study period covered publications between 2015 and 2025. Works in German and English that dealt with the key criteria specified in Figure 2 were included. The natural building materials wood (K1) and loam (K2) as well as ecological logistics buildings (K3) were examined independently of each other. In an initial screening, 271 articles were identified.

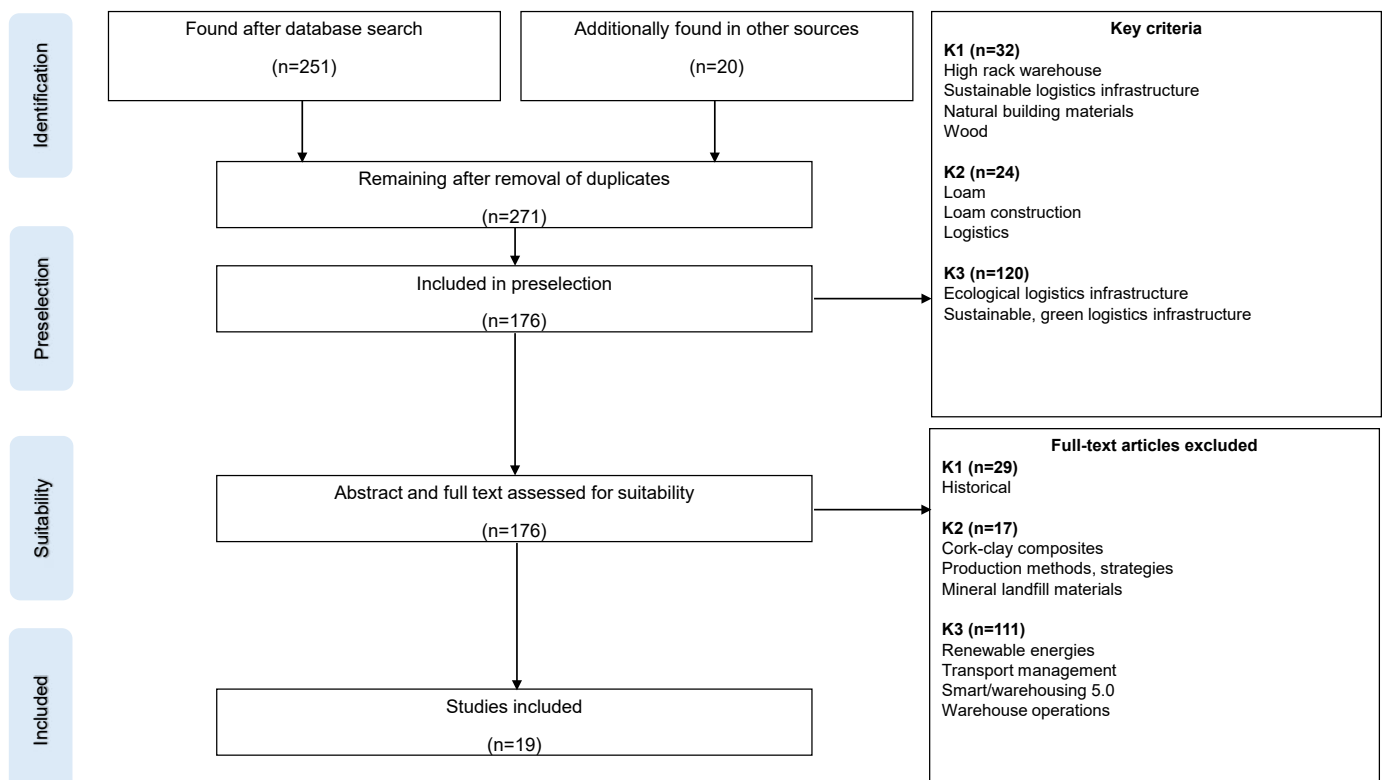
After reviewing the content based on title, abstract, and full text, 252 publications were excluded. These had no

relevant connection to logistics infrastructure or industrial buildings, dealt exclusively with a historical review of natural building materials, touched only on architectural or urban planning topics without any reference to materials, or did not contain sufficiently methodologically reliable results. A total of 19 articles covering ecological, technical, or economic evaluation aspects of natural building materials were included in the scientific evaluation.

Expert interviews

In addition to the literature review, guided expert interviews were conducted to obtain qualitative assessments of the technical, economic, and ecological suitability of natural building materials in logistics construction and to validate the theoretically determined evaluation criteria. Depending on the interviewee's field of expertise, the interview guide comprised ten to thirteen questions surrounding motivation for using natural

Figure 2: Graphical representation of the PRISMA method [9].



building materials, economic efficiency, technical suitability, ecological compatibility, and future potential.

A total of three interviews were conducted with experts from the construction industry (i1), research (i2), and architecture (i3) between April and May 2025. The interviews lasted 45 to 60 minutes each and were recorded and transcribed with the consent of the participants. For reasons of clarity and confidentiality, the interview guide and transcripts are not included in this article, but can be viewed on request.

Applied evaluation dimensions

Three dimensions are taken into account to form an overview of natural building materials in logistics infrastructure construction:

1. The ecological dimension assesses whether raw materials are processed before use, how quickly they renew themselves naturally, and to what extent they can be returned to the cycle after use.
2. The economic dimension compares the investment and life cycle costs incurred with conventional materials and weighs these against the potential benefits for corporate image and customer value.
3. The technical dimension examines the durability, load-bearing capacity, and versatility of the building materials to ensure their practical suitability for industrial construction.

Results on the potential of natural building materials in logistics infrastructure

The results from literature research and expert interviews aim to show the contribution that natural raw materials make to the sustainable design of logistics infrastructure and the specific role that loam and wood can play in the context of circular construction. Previous studies have shown that the choice and composition of building materials contribute significantly to the overall ecological balance of buildings [5]. Natural building materials can significantly reduce resource consumption due to their local availability, recyclability, and comparatively low environmental impact, thus representing a sustainable alternative to conventional materials [11].

In addition, current research shows that earthbound and biogenic materials are increasingly being optimized for industrial construction with the help of modern processes [12]. Building on these studies, the following sections examine the potential of loam and wood for use in logistics infrastructure in more detail.

Evaluation of loam in industrial construction

Natural regenerability and wide availability make loam a building material with great potential for circular construction [6]. In Austria, recent studies show that processed excavated soil can be used directly on the construction site as a wall-building material without a firing process, a resource-saving approach that reduces planning, construction, and transport costs during the construction phase and can be taken into account as early as the design phase [7]. Today, loam is mainly used in the form of load-bearing rammed earth constructions in combination with timber frame. This construction method was implemented in an exemplary manner for the Weleda Cradle Campus in Schwäbisch Gmünd: rammed earth walls made from local excavated material cover an area of approx. 2000 m² and perform both climatic and aesthetic functions by naturally integrating the building into the landscape [13, interview, May 20, 2025].

Ecologically, loam is almost ideal: unlike steel and concrete, it does not require energy-intensive production, is completely recyclable, and regulates the indoor climate during use and maintenance by storing moisture and heat [13]. At 21 kg CO₂e/m³, loam causes only a fraction of the greenhouse gas emissions of concrete at 197 kg CO₂e/m³ [14]. Loam not only reduces operating energy through natural climate control, but also creates a healthy indoor climate [i2, interview, May 14, 2025]. Finally, loam can be completely returned to the material cycle during the demolition phase: it can be crushed, moistened, and reused on site or returned to nature without pollutants, which is an essential criterion for recyclable logistics architecture [13].

There are still economic challenges: construction costs and times are often higher and longer than with conventional materials, particularly due to the high proportion of manual labor and lack of standardization in production [i1, interview, April 30, 2025]. In the long term, these can be offset by savings in operating costs during use, maintenance and demolition, especially since loam can be completely reused [13]. Increasing industrialization, for example in the form of modular production or robot-assisted loam construction, help to improve both the scalability and competitiveness of these construction methods [12].

Technically, loam can be used in structures that are load-bearing, such as exterior facades, as well as non-load-bearing, such as interior walls. For load-bearing applications, however, it must be combined with other materials such as wood or steel to ensure the necessary structural stability [i2, interview, May 14, 2025, i3, interview, May 20, 2025]. Studies show that adding natural fibers during the manufacturing process can also significantly improve mechanical strength [15, 16]. In outdoor applications, moisture protection is a key challenge: to

ensure structural integrity, targeted protective measures and careful structural planning are essential [17, 11].

Evaluation of wood for high rack warehouses

As a regionally available, renewable raw material with CO₂ storage potential, wood makes an important contribution to climate-friendly construction. However, wood has hardly been used in constructing logistics infrastructure to date, especially in the design of automated high rack warehouse systems. Even in the concept and planning phase, there is often a lack of established standards and experience, as the knowledge and expertise required to construct such facilities is limited to a few specialist companies [18].

One of the first companies to use timber construction in modern high rack warehouse systems is Alnatura. In Lorsch, the company built a high rack warehouse measuring approximately 9,000m² using timber construction methods. Since 2013, the logistics company Schachinger in Austria has also been operating an 11,760m² high rack warehouse made of timber, which sets standards in terms of building ecology, life cycle costs, energy efficiency, and workplace quality and has received multiple awards [3].

Wood is clearly superior to steel in terms of ecology. As a renewable raw material, wood causes significantly lower greenhouse gas emissions during the production of components. According to a study by the Technical University of Munich, replacing a steel high rack warehouse with a wooden one can save up to 1,600 tons of CO₂ equivalents, which corresponds to the annual emissions of around 1,000 cars [18]. Wood also scores highly in the dismantling, demolition, and disposal phase: it is highly recyclable and biodegradable [i3, interview, May 20, 2025].

For the vast majority of companies, the economic perspective is the deciding factor for feasibility. In many cases, the investment costs for timber high rack storage are higher than those for a standard steel structure. During the construction and implementation phase, higher material costs are primarily responsible, amounting to between 5% and 30% in completed projects [18]. In agricultural construction, wood can achieve a cost advantage of up to 12%, but remains economically inferior to steel under conventional conditions [18, 19]. Intangible economic advantages are also relevant. Companies with a strong focus on sustainability, such as Weleda and Alnatura, specifically choose wood as a building material in order to strengthen their sustainability profile [i2, interview, May 14, 2025].

From a technical point of view, wood can generally be used in logistics construction wherever moisture exposure is minimal. In terms of service life, wood is in no way inferior to steel as a building material when properly protected. The corrosion resistance and thermal insulation properties of wood offer additional advantages during

the use and maintenance phases. With suitable protective measures, even hazardous materials or open foodstuffs can be stored in wooden shelving systems. In terms of fire protection, wood is characterized by controllable fire behavior, which facilitates the planning and implementation of fire protection measures, although an increased number of sprinklers is usually required. It must also be taken into account that, in order to achieve a load-bearing capacity comparable to that of steel, wooden structures may require more material and alternative supply sources [18].

Final assessment

The summary analysis (**Fig. 3**) shows that loam and wood can play a central role in the sustainable transformation of logistics infrastructure. Loam is particularly impressive due to its recyclability, its potential for improving indoor climate, and the possibility of reuse from regional excavations. Wood offers high technical resilience and is particularly suitable for warehouse equipment, such as high rack warehouses. However, these materials also have limitations: the market availability and economic competitiveness of loam has been low so far. Its production is labor-intensive and not very industrialized, which inhibits scaling. Wood has proven itself technically sound but is yet to be widely used in the market for high rack warehouses. In the long term, the potential of both materials lies in their combination: loam for regulating indoor climate, wood as a CO₂ storage medium. Loam and wood thus not only contribute to the decarbonization of the construction and logistics industries, but also define central approaches for circular construction.

Research needs and recommendations

Several conclusions can be drawn for practice and research. Economic considerations remain the decisive criterion for the vast majority of companies. Standardized planning principles and technical guidelines are often lacking in construction implementation, which leads to additional costs, particularly in Germany. The scalability and automation of construction processes are still underdeveloped. However, industrial prefabrication could lead to cost reductions and greater marketability in the medium term.

Research is therefore needed to develop material-specific manufacturing technologies and recyclable connection solutions for logistics buildings, such as those being investigated in the "InDeckLe" project, a cooperation between Stuttgart University of Applied Sciences and Biberach University of Applied Sciences focused on hybrid ceiling systems made of loam and wood [i2, interview, May 14, 2025]. Although the use of loam and wood currently requires higher investments in the construction

Dimensions	Criterion	Loam		Wood	
		Rating	Reason	Rating	Reason
Ecology	Degree of processing	Good	No chemical additives, local excavation material can be used, mobile field production	Satisfactory	Partial industrial processing necessary (e.g., glued laminated timber), but no high energy consumption
	Regenerability	Very good	Fully renewable by moistening and reshaping	Good	Renewable raw material, can be recycled or used for thermal energy
	Recyclability	Very good	Almost completely recyclable, can also be used in conversions	Very good	Can be separated by type, can be used in many ways (e.g., as shelving or roof structure)
Economy	Investment costs	Poor	High project costs due to manual labor, special approvals, hardly any economies of scale	Satisfactory	Partially prefabricated, high modularity, but special solutions required for high racks
	Life cycle costs	Good	Very low maintenance, robust, easy to repair, no technical wear and tear	Very good	Durable, CO ₂ storage, reusability of modules reduces life cycle costs
	Reputation value	Very good	Image-building, tours, positive perception, CSR-compatible	Good	Competitive advantage through sustainable image, CSR signaling effect
Technical suitability	Durability	Satisfactory	Durable with careful construction, but sensitive to moisture	Good	Durable when constructed correctly; e.g., 30 m shelving structures possible
	Stability/safety	Satisfactory	Only load-bearing in combination with wood or concrete, not free-standing at great heights	Very good	Fully load-bearing (also for high rack warehouses); part of load-bearing systems
	Fields of application	Satisfactory	Versatile, but severely limited in mechanical/load-bearing and hygienic applications	Good	Versatile – load-bearing, facade, interior, roof, etc.

Figure 3: Tabular evaluation of natural building materials.

phase, these can be partially offset by savings in the use and maintenance phases. Greater awareness and long-term research are crucial for this shift in cost distribution within the life cycle.

The recommended course of action is as follows: In order to highlight the ecological potential of natural building materials in logistics, there must be a coordinated interaction between research, technical standardization, political support mechanisms, and the creation of a reliable regulatory framework. The Weleda Cradle Campus pilot project proves that the synergistic integration of natural building materials such as loam and wood is technically and creatively possible. In the future, hybrid natural building systems could become the reference model for a new generation of circular logistics infrastructure that is resilient, resource-efficient, and economically viable.

Bibliography

- [1] Rüdiger, D.; Dobers, K.; Ehrler, V.; Lewis, A.: Carbon footprinting of warehouses and distribution centers as part of road freight transport chains. In: 4th International Workshop on Sustainable Road Freight Transport. Cambridge 2017. DOI: 10.13140/RG.2.2.29764.32643.
- [2] Liebrich, C.; Fröhlich, S.: Industrielle Fertigung von großformatigen Lehmsteinen für nachhaltige und wirtschaftliche Gebäude. In: ce/papers (2023) 6, pp. 1624-1628. DOI: 10.1002/cepa.3001.
- [3] Deckert, C.: CSR und Logistik: Spannungsfelder Green Logistics und City-Logistik, 2nd edition. Berlin Heidelberg 2021.
- [4] McKinnon, A.; Browne, M.; Cullinane, S.; Whiteing, A.: Green logistics: improving the environmental sustainability of logistics, 3rd edition. London Philadelphia New Delhi 2015.
- [5] Ege, R.; Kornmann, M.; Stöver, C.; Uckelmann, D.: Ökologische Logistikgebäude: Ein Leitfaden für ein umweltorientiertes Lager - von der Planung bis zum Bau. In: Industrie 4.0 Management 35 (2019) 6, pp. 51-54. DOI: 10.30844/I40M_19-6_S51-54.
- [6] Löser, J. K.: Die Praxis des Nachhaltigen Bauens, 1st edition. Wiesbaden 2017. DOI: 10.1007/978-3-658-17566-5.
- [7] Korra, C.; Akshita Sadhana, V.: Green Warehouses: The Benefits, Challenges and Strategies of Industrial Building Decarbonization. In: International Journal of Innovative Science and Research Technology 9 (2024) 3, pp. 1454-1462. DOI: 10.38124/ijisrt/IJSRT24MAR1644.
- [8] Bortz, J.; Döring, N.: Forschungsmethoden und Evaluation: für Human- und Sozialwissenschaftler, 4th revised edition. Heidelberg 2006.
- [9] Page, M. J.; McKenzie, J. E.; Bossuyt, P. M.; Boutron, I.; Hoffmann, T. C. et al.: The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. In: BMJ (2021) 372 :n71. DOI: 10.1136/bmj.n71.
- [10] Hofmeister, S.; Arquitectos, M. R.; Bechter, G.; Boltshauser, R.; Heringer, A. et al.: Naturbaustoffe: 30x Architektur und Konstruktion: Bambus, Holz, Kork, Lehm, Naturstein, Reet, Seegrass, Stroh, 1st edition. Munich 2024. DOI: 10.11129/9783955536251.

- [11] Wagner, K.: Wasted ground – Die Potenziale von Aushub im Lehmbau. URL: <https://repositum.tuwien.at/bitstream/20.500.12708/198777/1/Wagner%20Karolin%20-%202024%20-%20Wasted%20ground%20-%202024%20-%20Wasted%20ground%20-%20Die%20Potenziale%20von%20Aushub%20im%20Lehmbau.pdf>, accessed 23.07.2025.
- [12] Bühler, M. M.; Hollenbach, P.; Michalski, A.; Meyer, S.; Birle, E. et al.: The Industrialisation of Sustainable Construction: A Transdisciplinary Approach to the Large Scale Introduction of Compacted Mineral Mixtures (CMMs) into Building Construction. In: Sustainability 15 (2023) 13, pp. 10677-10701. DOI: 10.3390/su151310677.
- [13] Schroeder, H.; Lemke, M.: Ökologische Bilanzierungen für Lehmabbaustoffe. In: Mauerwerk Kalender 2020: Bauen im Bestand Befestigungen Lehmabbaustoffe 45 (2020), pp. 39-62.
- [14] Huber, S.: Weiterentwicklung zirkulärer und automatisierter Bauweisen des modernen Lehmbaus - beispielhafte Untersuchungen der Stampflehmherstellung und des 3D-Drucks mit Lehm. URL: <https://opus.htwgkonstanz.de/frontdoor/deliver/index/docId/3491/file/MasterthesisSelinaHuber.pdf>, accessed 23.07.2025.
- [15] Parlato, M.; Rivera-Gómez, C.; Porto, S. M. C.: Reuse of livestock waste for the reinforcement of rammed-earth materials: investigation on mechanical performances. In: Journal of Agriculture Engineering (2023). DOI: 10.4081/jae.2023.1434.
- [16] Daube, L.: Strengthening Earthen Building Materials with Cellulose Fibers. In: ce/papers 8 (2025) 1, pp. 34-44. DOI: 10.1002/cepa.3289.
- [17] Pfau, J.: Leistungsfähigkeit gipsgebundener Bauplatten im Ausbau, Potential zur Substitution dieser Platten durch alternative Produkte. URL: <https://opus4.kobv.de/opus4-rosenheim/frontdoor/index/index/docId/2061>, accessed 23.07.2025.
- [18] Günthner, W. A.; Winter, S.; Ludwig, C.; Glaser, P.: Wirtschaftliche und ökologische Potenziale von Hochregallagern aus Holz. In: Günthner, W. A. (ed.): Lehrstuhl für Fördertechnik Materialfluss Logistik. Munich 2016.
- [19] Simon, J.; Oberhardt, F.; Jiang, Y.; Winter, S.; Helm, S. et al.: Holz beim Stallbau - beständig, nachhaltig und wirtschaftlich. In: Bautagung Raumberg-Gumpenstein 2021 (2021), pp. 75-81.

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Applied AI Ethics in the Workplace

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Issue 2/2026 of Industry 4.0 Science, "Industrial Learning Factories", will be published in April 2026.

Guidelines for the Fair Use of Generative AI

Generative AI offers both employment risks and potential benefits, such as productivity gains, for companies and employees. In order to harness the opportunities while avoiding negative effects, an AI usage strategy based on ethical guidelines is required. Two operational use cases are used to show how operational practitioners can use the 'FriendlyTechCheck' to identify potential benefits and risks of using ChatGPT for work and employment in companies. With a view to creating guidelines for the fair use of generative AI, the corresponding design implications for the humane and employment-promoting use of generative AI are discussed.

Anja Gerlmaier and Paul-Fiete Kramer (University of Duisburg-Essen), Dirk Marrenbach (Fraunhofer IAO), and René Wenzel (Iserlohner Werkstätten gGmbH)

Regulation of Human-Centered AI in Companies with Employee Representation

The introduction of AI systems in companies poses new challenges for regulation and co-determination. The 2025 EU AI Act provides binding requirements, which must be adapted nationally to comply with the Works Constitution Act (BetrVG). The regional competence center humAine has developed a model AI agreement in accordance with Section 77 BetrVG, which strengthens employee co-determination rights and implements

European regulations in a practical way. Flanked by co-determination dialogues, the model BV KI enables company-specific adaptation for responsible and human-centered AI use.

Alexander Ranft, Fabian Hoose, Claudia Niewerth, Mathias Preuß, and Manfred Wannöffel (Ruhr University Bochum)

Ethical AI in the Workplace via Value-Based Labels?

AI systems are increasingly supporting employees in complex decision-making processes. For these interactions to be successful, however, employees must be able to validly assess the trustworthiness of an AI-based recommendation. Innovative AI ethics labels have been designed to help employees make this assessment and promote the development of trustworthy AI solutions. The AI Ethics Impact Group has developed a label based on the VCIO framework (values, criteria, indicators, observables) that specifically addresses relevant ethical values. However, such labels are still not widely used, which is why there is little empirical data available regarding their application in real-world use cases. The practical feasibility and benefits of AI labels remain thus unclear.

Natalie Martin and Tobias Kopp (Karlsruhe University of Applied Sciences), Natalie Beyer (LAVRIO.solutions GmbH), Jochen Wendel (INIT GmbH), and Steffen Kinkel (Karlsruhe University of Applied Sciences)

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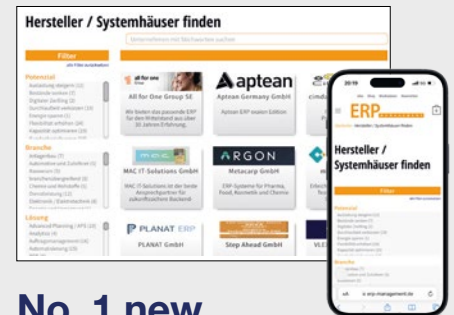
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