	EASI ZERo **GA n°101091531**
Deliverable	**BUILDABILITY REPORT**

Deliverable ID	**D5.5**
Deliverable name	**Buildability report**
Deliverable description	This deliverable discloses the buildability and disassembly of various wall constructions (wood frame, masonry, concrete). The installation procedures with regard to time and complexity of operations will be analyzed, with regards to high insulation performance, air and water tightness, durability. This results from task 5.4 experimental work.

WP	5	Performance evaluation in test environments
Task	5.4	Buildability of wall constructions

Dissemination level[1]	PU	**Due delivery date**	31/05/2026
Nature[2]	R	**Actual delivery date**	10/06/2026

Lead beneficiary	SINTEF
Proprietary project reference	NA
Proprietary document reference	NA
Contributing beneficiaries	SINTEF, USTUT, DTI, CEA, HUNTON, SQIM, INDRESMAT, LFB, MVIC

[1] Dissemination level: **PU** = Public, fully open, **SEN** = Sensitive, limited under the conditions of the Grant Agreement
[2] Nature of the Deliverable: **R** = Report

Version Management			
Filename	EZ0_D5.5_v2.1		
Author(s)	Nicola Lolli, Marina Stipetic		
Approved by task leader	Nicola Lolli	**Visa**	☑
Approved by WP leader	Alessandro Nocente	**Visa**	☑
Approved by Coordinator	Arnaud Jay	**Visa**	☑
Authorized by Coordinator	Arnaud Jay	**Visa**	☑

Version	Date	Author(s)	Modification[3]
V0	07.05.2026	Nicola Lolli	-
V0.1	15.05.2026	Amandine Piot, David Widmayer	Review
V0.2	09.06.2026	Naud Megens	Review
V1	10.06.2026	Nicola Lolli	Final version
V2.1	04.08.2026	Nicola Lolli	Revised version

EC-Grant Agreement	**101091531**
Project acronym	**EASI ZERo**
Program	HORIZON EUROPE
Client	HADEA
Start date of project	01 December 2022
Duration	42 months
Disclaimer	Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Health and Digital Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Coordinator – Administrative information	
Project Coordinator name	Jay Arnaud
Project Coordinator organization name	CEA
Address	CEA | INES campus | F-73375 Le Bourget-du-Lac
Phone Numbers	+33 4.79.79.21.84
Email	arnaud.jay@cea.fr
Project web-sites	www.easizero.eu

[3] Creation, Modifications, Final version for evaluation, Revised version following evaluation, Final.

Table of Content

1. EXECUTIVE SUMMARY 5

Description of the Deliverable content and objectives 5

Deviation from Objectives, Corrective Action 5

Technical Progress 5

1.1 Impact of the results 5

1.2 Dissemination Activities Carried Out / Planned 6

1.3

2. GOAL AND SCOPE OF TASK 5.4 7

1.4

3. METHOD 7

1.

Literature review 8

EZ0 assembly/disassembly performance assessment 12

3.1

3.2 SINTEF LAB mock-up 16

3.3 *3.3.1 Lab set-up description 20*

3.3.2 Assembly: overall elapsed time 21

3.3.3 Assembly: time performance and waste produced 24

3.3.4 Disassembly: time performance, waste and damaged elements 26

3.4

Description of case studies 28

3.4.1 USTUTT LAB mock-up 28

3.4.2 CEA Test facility 30

3.4.3 SINTEF Test facility 31

4.1

4. RESULTS 33

USTUTT LAB mock-up 33

4.2

4.1.1 Assembly 33

4.3 *4.1.2 Disassembly 37*

CEA Test facility 38

4.2.1 Assembly 38

SINTEF Test facility 39

5. CONCLUSIONS 39

Glossary

ABC: Activity-Based Costing
ALB: Assembly Line Balancing
CDF: Constructional Data Form
CIMOSA: Computer Integrated Manufacturing Open System Architecture
CPM: Critical Path Method
DECM: Disassembly Evaluation Chart Method
DES: Discrete Event Simulation
DfA: Design for Assembly
DfD: Design for Disassembly
DHM: Digital Human Modeling
eDiM: ease of Disassembly Metric
EZ0: EASI ZERo project
MODAPTS: Modular Arrangement of Predetermined Time Standards
MOST: Maynard Operation Sequence Technique
MTM: Methods Time Measurement
OEE: Overall Equipment Effectiveness
OWAS: Ovako Working Posture Analysis System
PMTS: Predetermined Motion Time System
REBA: Rapid Entire Body Assessment
RULA: Rapid Upper Limb Assessment
SAM: Standard Allowed Minute
SMED: Single-Minute Exchange of Dies
SWCT: Standard Work Combination Table
TDABC: Time-Driven Activity-Based Costing
VSM: Value Stream Mapping

1. Executive summary

Description of the Deliverable content and objectives

Deliverable D5.5. describes the procedures and results of the buildability construction assessment. Goal of Task 5.4 is to test the performance of the assembly and disassembly of the EZ0 wall constructions with respect to time and complexity of building operations. In Task 5.3, the EZ0
1.1 products were installed in test outdoor facilities (CEA and SINTEF) and in indoor wall constructions mock-ups (USTUTT, and SINTEF) to monitor and evaluate their technical performance (thermal transmittance, hygroscopic behavior, sound absorptance, etc). In synergy with the assembly and disassembly procedures performed in Task 5.3, the activities in Task 5.4 were arranged to gather information regarding the assembly and disassembly performances. This was to address additional parameters of performance of EZ0 products (time and easiness of operations) to their technical performance already evaluated in Task 5.3.

Deviation from Objectives, Corrective Action

1.2 No deviations

Technical Progress

1.3

Several tests were conducted in 4 different facilities on the assembly and disassembly procedures of EZ0 products. As per Objective 4 of EZ0 (easy, fast and reliable installation of panels, accessories and finishing materials) a KPI was identified with the target of reducing the installation time by 30%, to be verified by measurement at lab scale relative to standard renovation process. A comparative assessment between standard products and EZ0 products was carried out in the USTUTT lab test,
1.4 where hollow bricks were compared against insulated bricks (either with or without PCM).

Impact of the results

The time-action analysis showed that the installation of the insulated bricks (not including the mortar layering) was 3% shorter than that of the uninsulated bricks. This was due to a faster procedure for setting in place the bricks on the wall. The additional weight of the bricks did not significantly slow the installation process. When comparing the overall installation process (bricks and mortar) of PCM-insulated bricks and standard insulated bricks, the installation time of the former was 10% faster than the latter. When comparing the installation time of the aerogel-insulated render against a standard insulated render, the installation time of the former was 12% shorter than the latter. For the other products, a comparative test was not performed, and a corresponding time analysis was not carried out. The composition of the new wood-fiber panels did not change any characteristic of the product to alter its installation procedure and, therefore, its installation time is considered unaltered.

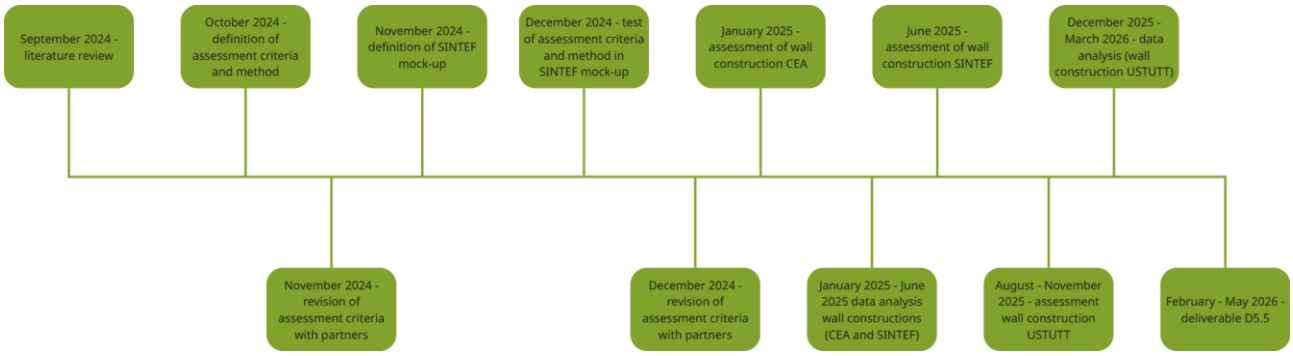
Dissemination Activities Carried Out / Planned

No planned dissemination activities

1.5

2. Goal and scope of Task 5.4

Goal of Task 5.4 is to test the performance of the assembly and disassembly of the EZ0 wall constructions with respect to time and complexity of building operations. In Task 5.3, the EZ0 products were installed in test outdoor facilities (CEA and SINTEF) and in indoor wall constructions mock-ups (USTUTT, and SINTEF) to monitor and evaluate their technical performance (thermal transmittance, hygroscopic behavior, sound absorptance, etc). In synergy with the assembly and disassembly procedures performed in Task 5.3, the activities in Task 5.4 were arranged to gather information regarding the assembly and disassembly performances. This was to address additional parameters of performance of EZ0 products (time and easiness of operations) to their technical performance already evaluated in Task 5.3. In order to do so, Task 5.4 started earlier than planned in the GAP to define the evaluation criteria and procedures for data collection in Task 5.4, in agreement with the EZ0 partners participating in Task 5.3. This was done to ensure the activities in Task 5.4 could be performed at the time the wall constructions were assembled, and therefore, collect relevant and updated inputs for their evaluation in Task 5.4. The following timeline summarizes the steps taken in Task 5.4.



3. Method

This section describes the method employed for the assembly and disassembly performance assessment, according to the following steps:

- A literature review was carried out to map applications and methods of time efficiency during products manufacturing operations and building construction operations. The literature review was used to define the most relevant methods with respect to the application in building construction.
- The mapped methods and applications were evaluated in relation to their adaptation to the context of building construction and specifically to lab testing conditions (as described in Task 5.3).
- The led to the development of the assessment methodology used in Task 5.4. This was devised as a guided fillable form, to be populated with information regarding assembly and

disassembly procedures, construction layers, time of operation for each layer, difficulty of operation for each layer, etc.

- The defined assessment method was then tested on a simulation of a wall renovation applied to a full-scale wall construction mock-up (carried out in SINTEF laboratory and henceforth called SINTEF LAB mock-up)
- These results were then used to revise the assessment methodology, which was handed out to the partners. Further comments from the partners were used to finalize the assessment methodology.
- The finalized assessment guideline was handed over to the partners, filled, returned to SINTEF, and data was analyzed.

Literature review

3.1 A literature review of applications of PMTS was carried out to analyze the methodologies of applications of such methods and their relevance to EZ0 activities in Task 5.3. PMTS is a family of systems employed to determine and assign times to specified basic motions during working operations, whose motions and associated times are catalogued. Work measurement is defined by establishing the best basic motion pattern for a certain task and, from the catalogue or data card, assigning the appropriate predetermined time. Since the times for all motions are predetermined, the overall time performance can be predicted for future tasks. Part of this family, MTM was the first predetermined motion time system with a very accurate and detailed data card of basic motions (reach; move; grasp; position; release; body, leg and foot motions; and so on) and associated times. It was developed in 1948 by Harold B. Maynard, G. J. Stegemerten and J. L. Schwab. Simplified versions of MTMs such as MTM-1, MTM-2, and MTM-3 were then developed to reduce analysis errors and time, by grouping and averaging certain basic motions and associated times, thus reducing the analysis time. The time analysis of work in specific industrial contexts, where highly repetitive and short-cycle operations occur, is performed with PMTS by systematically breaking work down into very small and distinct units called basic motions. In industrial context, where working operations are carried out with less repetitive operations, a very detailed approach requires a large time-effort for data analysis. To overcome this drawback, MOST was developed to be applied in general industrial working routines.

PMTS can be further implemented or support modelling techniques, metrics, and or assessment methods of industrial systems and processes, such as:

- DES, used to understand how a system operates over time, by modelling a system as a sequence of discrete events. The precise task times derived from a PMTS analysis can serve as critical input data for a Discrete Event Simulation.
- Cellular Manufacturing, in which a product is assembled by grouping together families of parts within a single line or cell of machines.
- eDiM, a systematic method used to calculate how long it takes to disassemble a product. Its primary purpose is to provide a clear, objective, and verifiable metric to evaluate and

improve product designs for a circular economy—making them easier to repair, reuse, and recycle.

- DECM, which provides a structured, step-by-step process for quantifying and improving a product's design for disassembly.
- TDABC, ABC, and cost management methodology which assign resource costs to cost objects (like products, customers, or services) based on the time required to perform activities.
- SAM, a work measurement unit used to express the time (in minutes) that a qualified worker, working at a normal pace, should take to complete a specific task or operation. SAM is often determined using Predetermined Motion Time Systems (PMTS).
- DHM, to create and simulate detailed, virtual representations of the human body and to analyse and optimize the interaction between humans and their environment, such as workplaces or products. These systems allow designers and engineers to predict human performance, comfort, and safety entirely within a digital environment, before the physical prototype is built.
- DfD, a product design approach that intentionally plans for the future separation of a product's components, materials, and systems at the end of its useful life . The core idea is to make products easier to take apart so that parts can be repaired, reused, remanufactured, or recycled, rather than simply being thrown away as waste.

Table 1 below summarizes the bibliographic references included in the literature review, the methods of assessment used, and the field of application.

Table 1. List of bibliographic references

Authors	Application	Method / process / metric	Product / producer
Abdulatif, N.; Yasser, S.; Fahim, I.; Emad, Y.; Saleh, A.; Kassem, S. Decision Support Using Simulation to Improve Productivity: A Case Study. In Proceedings of the 2020 International Conference on Decision Aid Sciences and Application (DASA); IEEE: Sakheer, Bahrain, November 8 2020; pp. 1120–1127.	Assembly line in manufacturing	MOST, ALB	AC units
Abdullah, R.; Abdul Rahman, Md.N.; Salleh, Mohd.R. A Systematic Approach to Model Human System in Cellular Manufacturing. JAMDSM 2019, 13, JAMDSM0001–JAMDSM0001, doi:10.1299/jamdsm.2019jamdsm0001.	Assembly line in manufacturing	MOST, CIMOSA, cellular manufacturing	semiconductor
Boix Rodríguez, N.; Favi, C. Disassembly and Repairability of Mechatronic Products: Insight for Engineering Design. Journal of Mechanical Design 2024, 146, 020906, doi:10.1115/1.4064075.	Disassembly	MOST, EDIM	electric oven
Boks, C.B.; Kroll, E.; Brouwers, W.C.J.; Stevels, A.L.N. Disassembly Modeling: Two Applications to a Philips 21" Television Set. In Proceedings of the Proceedings of the 1996 IEEE International Symposium on Electronics and the Environment. ISEE-1996; IEEE: Dallas, TX, USA, 1996; pp. 224–229.	Disassembly	MOST, DFD	TV
Bures, M.; Pivodova, P. Comparison of the Predetermined Time Systems MTM-1 and BasicMOST in Assembly Production. In Proceedings of the 2013 IEEE International Conference on Industrial Engineering and Engineering Management; IEEE: Bangkok, Thailand, December 2013; pp. 546–550.	Assembly line in manufacturing	MOST, MTM-1	not specified
Chu, X.; Li, L.; Zhao, F.; Sutherland, J.W.; Yin, F. Disassembly Time Estimation for Used Smartphones Based on Maynard Operation Sequence Technology. Computers & Industrial Engineering 2024, 193, 110291, doi:10.1016/j.cie.2024.110291.	Disassembly	improved MOST	smartphones
De Fazio, F.; Bakker, C.; Flipsen, B.; Balkenende, R. The Disassembly Map: A New Method to Enhance Design for Product Repairability. Journal of Cleaner Production 2021, 320, 128552, doi:10.1016/j.jclepro.2021.128552.	Disassembly	MOST, EDIM	vacuum cleaner

Elnekave *, M.; Gilad, I. Rapid Video-Based Analysis System for Advanced Work Measurement. International Journal of Production Research 2006, 44, 271–290, doi:10.1080/00207540500160920.	Assembly line in manufacturing	MOST, PMTS	aluminium production, paper calendar assembly, pamphlet collection, load/unload converyor
Fang, Y. A Method of Meta-Mechanism Combination and Replacement Based on Motion Study. Production & Manufacturing Research 2015, 3, 310–323, doi:10.1080/21693277.2015.1093437.	Assembly line in manufacturing	MOST, motion analysis	PlayStation4 assembly
Fatmawati, W.; Razak, A.A. Analysis of Product Disassemblability Using the Disassembly Evaluation Chart Methodology. Mechanical Engineering 2008.	Disassembly	DFD, DECM	PC case
Formentini, G.; Ramanujan, D. Accounting For Product End-of-Life Status in Disassembly Time Estimation Using Modified Maynard Operation Sequences. Procedia CIRP 2023, 116, 305–311, doi:10.1016/j.procir.2023.02.052.	Disassembly	MOST, DfD	electrical kettle
Formentini, G.; Ramanujan, D. Design for Circular Disassembly: Evaluating the Impacts of Product End-of-Life Status on Circularity through the Parent-Action-Child Model. Journal of Cleaner Production 2023, 405, 137009, doi:10.1016/j.jclepro.2023.137009.	Disassembly	MOST, DFD	electrical kettle
Ganorkar, A.B.; Lakhe, R.R.; Agrawal, K.N. TIME DRIVEN ACTIVITY BASED COSTING (TDABC) MODEL FOR COST ESTIMATION OF WELDING PROCESS FOR A SSI. IEJ 2018, 10, doi:10.26488/IEJ.10.9.62.	Small manufacturing	MOST, TDABC	Steel welding
Geda, M.W.; Kwong, C.K.; Jiang, H. Fastening Method Selection with Simultaneous Consideration of Product Assembly and Disassembly from a Remanufacturing Perspective. Int J Adv Manuf Technol 2019, 101, 1481–1493, doi:10.1007/s00170-018-3027-1.	Disassembly	MOST	PC case
Golabchi, A.; Han, S.; AbouRizk, S.; Kanerva, J. Micro-Motion Level Simulation for Efficiency Analysis and Duration Estimation of Manual Operations. Automation in Construction 2016, 71, 443–452, doi:10.1016/j.autcon.2016.08.028.	Building construction	PMTS, MOST	concrete blocks production
Golabchi, A.; Han, S.; AbouRizk, S.M. INTEGRATION OF PREDETERMINED MOTION TIME SYSTEMS INTO SIMULATION MODELING OF MANUAL CONSTRUCTION OPERATIONS.	Assembly line in manufacturing	MODAPTS, PMTS	steel manufacturing
Hanash, E.A.H.; Karim, A.N.M.; Tuan, S.T.; Mohiuddin, A.K.M. Throughput Enhancement of Car Exhaust Fabrication Line by Applying MOST. IOP Conf. Ser.: Mater. Sci. Eng. 2017, 184, 012022, doi:10.1088/1757-899X/184/1/012022.	Assembly line in manufacturing	MOST, ALB	car exhaust
Harari, Y.; Riemer, R.; Bechar, A. Factors Determining Workers' Pace While Conducting Continuous Sequential Lifting, Carrying, and Lowering Tasks. Applied Ergonomics 2018, 67, 61–70, doi:10.1016/j.apergo.2017.09.003.	Lab	MTM-1, MOST	lifting/carrying boxes
J, G.M.; Gogi, V.S.; Aradhya, I.N.; Shankaramma Digitalization of Lean Tools and Techniques: Enhancing Efficiency and Quality in Modern Industries. In Proceedings of the 2024 8th International Conference on Computational System and Information Technology for Sustainable Solutions (CSITSS); IEEE: Bengaluru, India, November 7 2024; pp. 1–6.	Assembly line in manufacturing	LEAN methodologies—including VSM, Heijunka, Kanban, Gemba, Jidoka, Hoshin Kanri, Poka-Yoke, 5S, Spaghetti Diagrams, SWCT, Shojinka, SMED, and Kanban Blitz, MOST	Toyota, Ford, Amazon, Boeing, Boston Medical Center, Starbucks, Honda, Nestlé, General Electric, Intel, Kaiser Permanente, and Mayo Clinic.
Jiao, J.; Tseng, M.M. A Pragmatic Approach to Product Costing Based on Standard Time Estimation. International Journal of Operations & Production Management 1999, 19, 738–755, doi:10.1108/01443579910271692.	Assembly line in manufacturing	CDF, TER, CER, MOST	heath sink
Jing, S.; Shaohua, D.; Hui, P.; Bo, L. Optimal Designing of Distribution Center Operation Process. TOCSJ 2015, 9, 2229–2236, doi:10.2174/1874110X01509012229.	logistics	MOST	box sorting
KURKIN, O[ndrej] & BURES, M[arek]	Assembly line	MTM-1, UAS, MOST	packaging
Kim, J.; Golabchi, A.; Han, S.; Lee, D.-E. Manual Operation Simulation Using Motion-Time Analysis toward Labor Productivity Estimation: A Case Study of Concrete Pouring Operations. Automation in Construction 2021, 126, 103669, doi:10.1016/j.autcon.2021.103669.	Building construction	PMTS, MTM-1, MOST	Pouring concrete on deck
Kroll, E.; Hanft, T.A. Quantitative Evaluation of Product Disassembly for Recycling. Research in Engineering Design 1998, 10, 1–14, doi:10.1007/BF01580266.	Disassembly	DfD. MOST	PC case
Laring, J.; Forsman, M.; Kadefors, R.; Örtengren, R. MTM-Based Ergonomic Workload Analysis. International Journal of Industrial Ergonomics 2002, 30, 135–148, doi:10.1016/S0169-8141(02)00091-4.	Assembly line in manufacturing	MTM, SAM, VIDAR, MOST	automotive

Mazareinezhad, F.; Sekkay, F.; Imbeau, D. Evaluating the Accuracy of the MOST Predetermined Motion Time System through Lab Experiments.; 2024.	Lab	PMTS, Fitt's law, MOST	lab tests
Mazareinezhad, F.; Sekkay, F.; Imbeau, D. Development of a Framework to Implement Time Analysis in Digital Human Modeling Systems Using Predetermined Motion Time Systems. Discov Appl Sci 2025, 7, 356, doi:10.1007/s42452-025-06813-9.	Assembly line in manufacturing	DHM, PMTS, MOST	Dassault Systèmes Canada
Mazareinezhad, F.; Sekkay, F.; Imbeau, D. Improving Time Estimation Accuracy in Manufacturing Systems: Experimental Assessment of MOST Predetermined Motion Time System Using Laboratory Data and Fitts' Law. Int J Adv Manuf Technol 2025, 138, 4721–4737, doi:10.1007/s00170-025-15791-6.	Assembly line in manufacturing	DHM, PMTS, MOST	Dassault Systèmes Canada
Mazareinezhad, F.; Sekkay, F.; Imbeau, D. Field Validation of MOST and a DHM-Based Time Estimation Method Using Real-World Manufacturing Data. Int J Adv Manuf Technol 2025, 139, 2465–2479, doi:10.1007/s00170-025-16026-4.	Assembly line in manufacturing	DHM, PMTS, MOST	Dassault Systèmes Canada
Omega, D.; Andika, A. Improving Overall Equipment Effectiveness Using CPM and MOST: A Case Study of an Indonesian Pharmaceutical Company. IOP Conf. Ser.: Earth Environ. Sci. 2017, 101, 012039, doi:10.1088/1755-1315/101/1/012039.	Assembly line	OEE, CPM, MOST	cleaning process of machine, pharmaceutical production
Perumal, P.A.; Teruaki, I.; Siang, T.Y.; Sieng, Y.S. Examination of Overall Equipment Effectiveness (OEE) in Term of Maynard's Operation Sequence Technique (MOST). American Journal of Applied Sciences 2016, 13, 1214–1220, doi:10.3844/ajassp.2016.1214.1220.	Assembly line in manufacturing	OEE, MOST	semiconductor
Prakashbhai, P.S.; Patel, A.S. Time and Motion Study of Construction Activities in Industrial Building. 2020, 07.	Building construction	TMS	building construction
Razmi, J.; Shakhs-Niyaee, M. Developing a Specific Predetermined Time Study Approach: An Empirical Study in a Car Industry. Production Planning & Control 2008, 19, 454–460, doi:10.1080/09537280802052028.	Assembly line in manufacturing	PMTS, TMS, MOST	automotive
Rodríguez, N.B.; Gabriel, C.; Gaha, R.; Favi, C. Analysis of Disassembly Parameters in Repairability Scores: Limitations for Engineering Design and Suggestions for Improvement. Procedia CIRP 2023, 116, 738–743, doi:10.1016/j.procir.2023.02.124.	Disassembly	MOST, EDIM, RSS	cooking appliances
SAMON, J.B. Using Work Factor Method with the MOST System for Accurate Disassembly Time Evaluation. International Journal of Innovative Science and Research Technology 2021, 6.	Disassembly	WFM, MOST	DfD
Senny; Faghlefi, M.A.; Wijaya, D.I.; Tan, H.-S. Implementation of SMED Techniques to Improve Machine Capacity and Work Posture Analysis Using OWAS: A Case Study in Steel Company. IOP Conf. Ser.: Earth Environ. Sci. 2021, 794, 012098, doi:10.1088/1755-1315/794/1/012098.	Assembly line in manufacturing	SMED, OWAS, MOST	steel production
Shawky, W.; Seif-Elnasr, S.; Samy, I. Analysis of Musculoskeletal Disorders in Personal Care Industries in Egypt. In Proceedings of the 2019 Novel Intelligent and Leading Emerging Sciences Conference (NILES); IEEE: Giza, Egypt, October 2019; pp. 13–16.	Assembly line in manufacturing	RULA, REBA, MOST	soap production
Shukla, H.M.; Ganvir, K.D.; Joshi, M.P.; Gupta, I. Revamping Machining Operator Allowances through Standard Time Estimation Using MOST Technique. In Proceedings of the 2023 14th International Conference on Computing Communication and Networking Technologies (ICCCNT); IEEE: Delhi, India, July 6 2023; pp. 1–6.	Assembly line in manufacturing	MOST and TMS	steel plates
Sidanta, G.K.; Susanto, N.; Mahachandra, M. Case Study: Knowledge Management System (KMS) Using the Maynard Operation Sequence Technique (MOST) Approach to Improve Manufacturing Efficiency at CV. XYZ Leathercraft. In Proceedings of the Proceedings of the International Conference on Industrial Engineering and Operations Management; IEOM Society International: Sao Paulo, Brazil, April 5 2021; pp. 1692–1702.	Assembly line in manufacturing	KMS, MOST	leather manufacturing
Singh, B.; Singh, J.; Farwaha, H.S.; Singh, P.; Ranjan, N. Implementation of Maynard Operation Sequence Technique in an Engine Manufacturing Industry: A Case Study. J. Inst. Eng. India Ser. C 2025, doi:10.1007/s40032-025-01243-3.	Assembly line in manufacturing	MOST and TMS	tractor engines
Soham Ravishekhar Deshpande; Shri Ramdeobaba College of Engineering and Management, Nagpur An Overview on Lean Application Methods for Produvtivity Improvement. IJERT 2020, V9, IJERTV9IS020115, doi:10.17577/IJERTV9IS020115.	method comparison	value stream mapping, single minute exchange of dies, overall equipment efficiency, cellular manufacturing, assembly line balancing, Kanban, total productive maintenance, MOST	Not specified

Thakre, A.R.; Jolhe, D.A.; Gawande, A.C. Minimization of Engine Assembly Time by Elimination of Unproductive Activities through "MOST." In Proceedings of the 2009 Second International Conference on Emerging Trends in Engineering & Technology; IEEE: Nagpur, India, 2009; pp. 785–789.	Assembly line in manufacturing	MOST	tractor engines
Tuan, S.T.; Karim, A.; Kays, H.E.; Amin, A.; Hasan, M. Improvement of Workflow and Productivity through Application of Maynard Operation Sequence Technique (MOST).; 2014; pp. 7–9.	Assembly line in manufacturing	MOST and assembly cycle time	automotive
Vanegas, P.; Peeters, J.R.; Cattrysse, D.; Tecchio, P.; Ardente, F.; Mathieux, F.; Dewulf, W.; Duflou, J.R. Ease of Disassembly of Products to Support Circular Economy Strategies. Resources, Conservation and Recycling 2018, 135, 323–334, doi:10.1016/j.resconrec.2017.06.022.	Disassembly	MOST and EDIM	LCD monitor
Wang, J.; Li, X.; Han, S.; Al-Hussein, M. 3D Standard Motion Time-Based Ergonomic Risk Analysis for Workplace Design in Modular Construction. Automation in Construction 2023, 147, 104738, doi:10.1016/j.autcon.2022.104738.	Assembly line in manufacturing	REBA, RULA, MOST	window manufacturing
Wang, J.; Mohamed, Y.; Han, S.; Li, X.; Al-Hussein, M. 3D Ergonomics-Based Motion-Level Productivity Analysis for Intelligent Manufacturing in Industrialized Construction. Can. J. Civ. Eng. 2023, 50, 197–209, doi:10.1139/cjce-2022-0090.	Lab	MTM-1, REBA, RULA	Not specified
Xiao, J.; Huang, K.; Terzi, S.; Bandinelli, R. Towards Uncertainty of End-of-Use Product Recycling: A General Screw Connection-Oriented Disassembly Analysis. International Journal of Production Research 2025, 1–24, doi:10.1080/00207543.2025.2507111.	Disassembly	MOST	EV battery
Yadav, D.P.; Patel, D.N.; Morkos, B.W. Development of Product Recyclability Index Utilizing Design for Assembly and Disassembly Principles. Journal of Manufacturing Science and Engineering 2018, 140, 031015, doi:10.1115/1.4038515.	Disassembly	DFA	printer head

3.2 *EZ0 assembly/disassembly performance assessment*

Based on the literature review, the following key parameters were identified to define the evaluation method to be used in EZ0:

- Time of operation, to identify the most time consuming and complex operations.
- Tools used and number of tools, to assess if time-consuming operations are due to many tools, and if human-induced failures during the installation/uninstallation procedure are due to the tool used. To identify potential simplification of variety of tools used.
- Disassembly procedure: sequential or parallel operations. To identify which operations can be carried out concurrently to achieve a full disassembly of the EZ0 constructions.
- Difficulty of the task. To identify if human-induced failures are because of difficult operations.
- Comfort of the operator during task. To identify if uncomfortable positions of the operator make the operation more difficult to be performed, and to identify if human-induced failures are because of uncomfortable positions of the operator.
- Damaged elements, to assess rate of failures at separating all the elements (both mechanical and chemical bonding).

The key evaluation parameters were then integrated in the assessment evaluation form to be sent out to the EZ0 partners. The evaluation form was developed to record data during the assembly and disassembly procedures, and it was divided into 5 parts.

Part A: general information. In this part, general information of the assembly/disassembly process is requested, and it is meant as a check list of data collection steps for the EZ0 partners.

A	**General**	
A.1	Partner/Pilot name	
	(write)	
A.2	Name of the wall you assess in this form	
	(write)	
A.3	Have you provided the video recording with timestamp?	(select)
	Applications for video recording with timestamp are available for Android and Apple phones in their respective app	
A.4	Have you provided the drawing and details of walls assembly?	(select)
A.5	Have you provided the Bill of Quantities of the wall assembly?	(select)

Figure 1. Part A of the assessment form.

Part B: description of the preparatory steps. In this part, the EZ0 partners are asked to fill in information regarding the preparatory steps taken before the commencement of the assembly/disassembly operation. This information is needed because the building operations are carried out in laboratory environments, and not in real working conditions, and therefore it was necessary to separate the time for the preparatory steps from the time used for the actual assembly/disassembly procedures.

B	**About the preparatory steps**	
	Preparatory steps are all the operations that are necessary before the diassembly can start. It includes planning and gathering the necessary equipment of the disassmbly.	
B.1	How many people have participated the preparatory steps?	(write)
B.2	How much time did the preparation operations take? [hh:mm:ss]	0:00:00
B.3	Please summarise the preparatory steps you took, including the name of the equipment, machinery, and tools.	
	(write)	
B.4	Please describe the storage solution for the disassembled wall elements, if any, including the distance from the disassembly site .	
	(write)	

Figure 2. Part B of the assessment form.

Part C: overall description of the disassembly operation. In this part the EZ0 partners are asked to give an overall feedback with respect to time and difficulty of the assembly/disassembly operation. The EZ0 partners were asked to fill in such information by interviewing the operators hired for the construction.

C About the disassembly operations

The disassembly covers all the operation after the preparatory steps and before transporting the elements to another location (for example of a storage ara).

C.1	How many people have participated to the disassembly operations?	(write)
C.2	How much time did it take to completely disassemble the wall? [h:mm:ss]	0:00:00
C.3	Please summarise the disassembly steps you took.	(write)
C.4	How would you evaluate the disassembly process overall?	(select)
C.5	Do you have any comment about the easiness of disassembly process?	(write)
C.6	Once you have completed the disassembly, is there anything you would have done differently?	(write)
C.7	Estimate the volume [m3] occupied by the elements after disassembly.	(write) m3

Figure 3. Part C of the assessment form.

Part D: description of the disassembly process, layer by layer. In this last part, the EZ0 partners were asked to fill in information regarding spent time, number and type of tools, ratio of damaged elements, waste sorting of damaged elements, and difficulty to access and operation for each layer of the construction. Questions D.9 to D.12 were devised as a short questionnaire to be administered to the workers during or just after the completion of the operation and were aimed at understanding if complex or hidden connectors influence the share of damaged elements (question D.6) and the time to perform the operation (question D.5). To have a common understanding of layers subdivision of the EZ0 constructions, a simplified schematic was given to the EZ0 partners, showing that each layer was intended as a functional element of the construction, and therefore should be treated separately in Part D of the assessment form.

D	Layer-by-layer disassembly process					
			Layers of the wall assembly from outside to inside			
		Outdoor	Layer 1	Layer 2	Layer 3	Layer 4
D.1	Provide the name of each layer in each column (e.g., cladding, vapour barrier)		(write)	(write)	(write)	(write)
D.2	Please describe the **connectors** between Layer X and Layer X+1 (e.g. screws, glue).		(write)	(write)	(write)	(write)
D.3	How many **connectors** did you **loose or break** during the disassembly of Layer X?		0 %	0 %	0 %	0 %
D.4	Please list the different **tools** you used disassemble Layer X.		(write)	(write)	(write)	(write)
D.5	**Time [h:mm:ss]** it took to completely disassemble Layer X.		0:00:00	0:00:00	0:00:00	0:00:00
D.6	What is the **ratio [%, in weight]** of visibly damaged elements over the total weight of Layer X? Damaged elements are elements that cannot be used again as they are.		0 %	0 %	0 %	0 %
D.7	What did you do with the damaged elements, if any? (optional)		(select)	(select)	(select)	(select)
	D7.1 If "4-Throw them away to mixed waste", what is the current practice in your region for this type of waste? (optional)		(select)	(select)	(select)	(select)
D.8	What is the **ratio [%, in weight]** of disassembled elements that **are not** in standard dimensions (elements that have been cut or adapted on site)?		0 %	0 %	0 %	0 %
D.9	How easy was it **to access** the element of Layer X and all the connections of Layer X to the next layer?		(select)	(select)	(select)	(select)
D.10	Any comment about the easiness to access connectors and elements on each layer? (optional)		(write)	(write)	(write)	(write)
D.11	How easy was it **to disassemble** Layer X?		(select)	(select)	(select)	(select)
D.12	Any comment about the easiness of the disassembly for Layer X? (optional)		(write)	(write)	(write)	(write)
D.13	Is there any regulatory barrier in your country or region which make the undammaged element non reusable for		(select)	(select)	(select)	(select)

Figure 4. Part D of the assessment form.

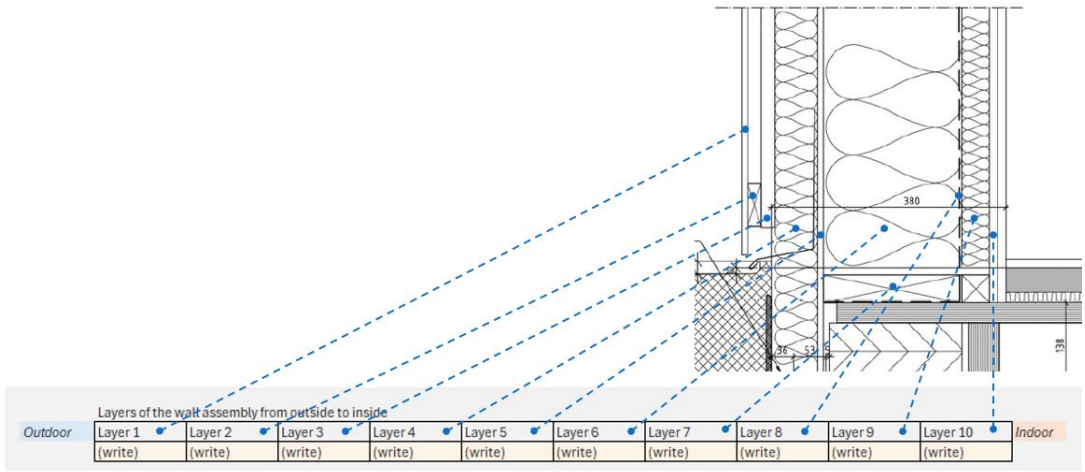


Figure 5. Example of layers identification for a wall construction.

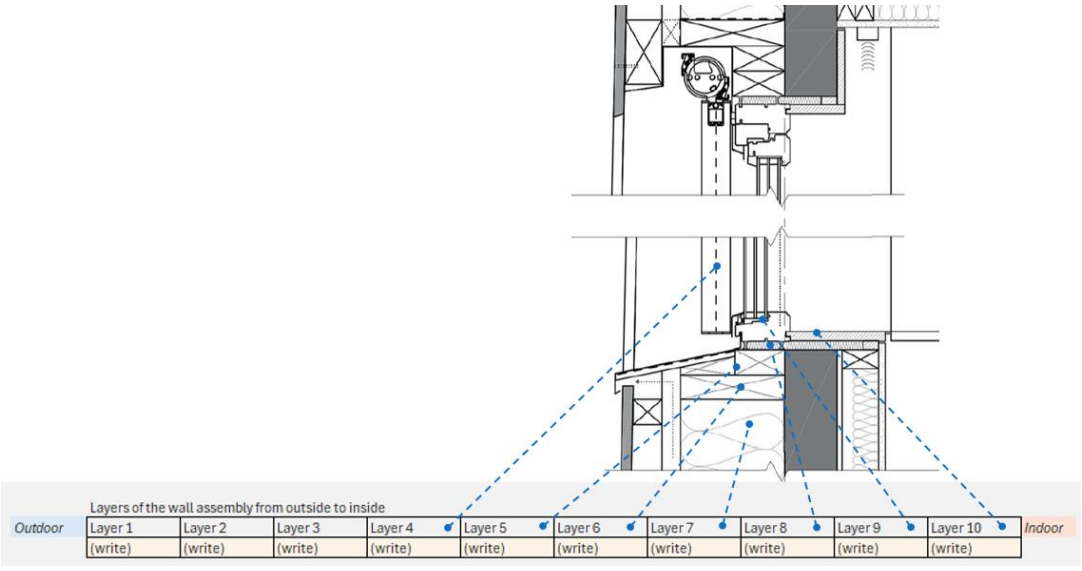


Figure 6. example of layers identification for a window.

SINTEF LAB mock-up

The assessment form was tested during the construction of a mock-up wall in the SINTEF laboratory in Trondheim, in December 2024. It was decided to replicate typical timber frame constructions from the period 1950-1969, being the one most representative for the number of residential units (detached houses and rowhouses) built in this period. Based on the Norwegian building standards enforced in that period, timber frame walls were insulated with 10 cm mineral wool insulation. This increased to 15 cm in the 1970s with the new building regulation issued in 1969. Table 2 below shows the percentage of total mass of residential unit per year range.

3.3

Table 2. Detached and rowhouses in Norway for number of units and relative share.

Detached houses, rowhouses	Number of units	Share of the total
1900 and earlier	116 147	6 %
1901-1920	67 539	4 %
1921-1940	103 735	6 %
1941-1945	9 988	1 %
1946-1960	250 357	13 %
1961-1970	208 641	11 %
1971-1980	282 263	15 %
1981-1990	262 540	14 %
1991-2000	158 255	8 %
2001-2010	157 631	8 %
2011-2020	147 244	8 %
2021 and after	36 321	2 %
Unknown	68 983	4 %
Total	1 869 644	100%

A reference wall of 4 m by 2.5 m was built as a gable end without windows. This wall construction was used as the starting point to simulate two renovation scenarios, based on a market-available product and on an EZ0 product and following current practices of timber frame renovation:

A. Rigid mineral wool panels are fixed on the reference wall timber frame by screws and spacers.
B. An additional timber frame is built adjacent to the reference wall and wood fiber insulation (produced by Hunton) is lodged between the posts.

In both renovation scenarios, the wall is finished with a vapor barrier and wood cladding. The removal of cladding, boards, finishing, etc. from the existing wall was not simulated, as this was not relevant for the test. The starting point was therefore the bare construction, ready for it to be insulated and finished. Figure 9 and Table 3 describe the construction of the reference wall and the amount of materials bought to build it. Figure 10 and Table 4, and Figure 11 and Table 5 describe the technical details of the construction and the bill of quantities of the retrofitting solutions with the renovation scenario A and B, respectively. A local construction company, specialized in housing renovations, was hired to perform the assembly and disassembly of both the renovation scenarios. The reference wall was built by SINTEF lab personnel.

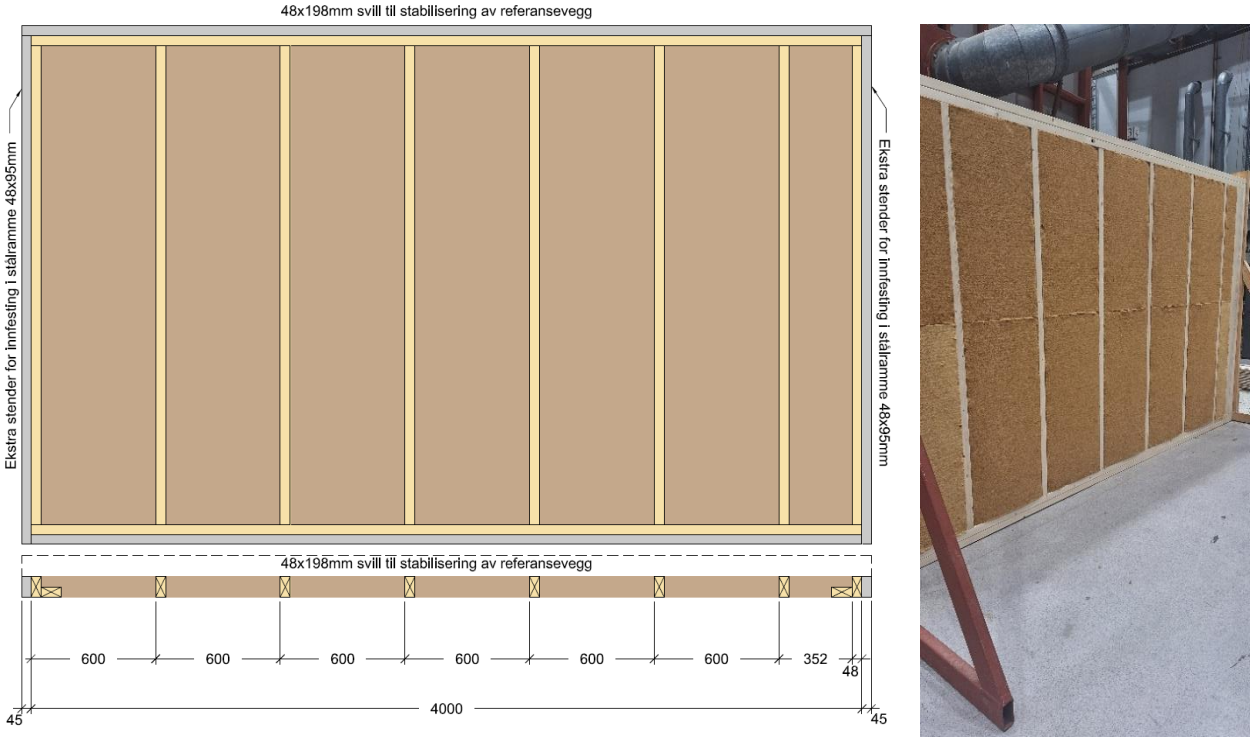


Figure 7. Technical drawing and image of the built reference wall.

Table 3. Materials bought for the reference wall.

Material	Total amount	Unit
Timber 48x198 mm	8.4	m
Timber 48x98 mm	32.4	m
Wood fibre insulation 100 mm	10	m^2
Chipboard 12 mm	4	board
Screws 5x90 mm	1	bag

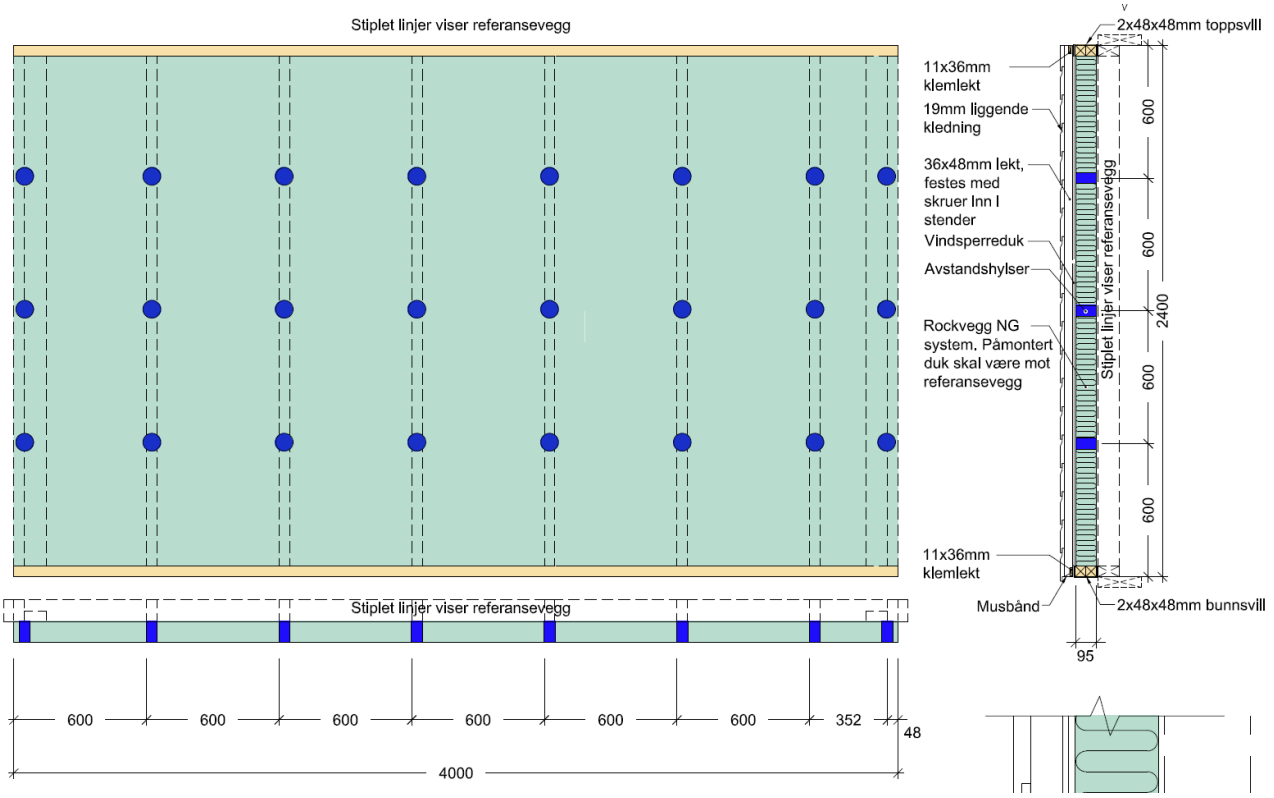


Figure 8. Technical drawing of the renovation scenario A.

Table 4. Materials bought for renovation scenario A.

Material	Total amount	Unit
Timber 48x48 mm	16.8	m
Mineral wool plates 100 mm	10	m^2
Spacers	30	pieces
Wind barrier	10	m^2
Timber 36x48 mm	19.2	m
Timber 11x36 mm	8.4	m
Mouse barrier	4.2	m
Wood cladding 19x149 mm	79.7	m
Screws 6x180 mm	1	bag
Screws 4,4x52 mm	1	bag

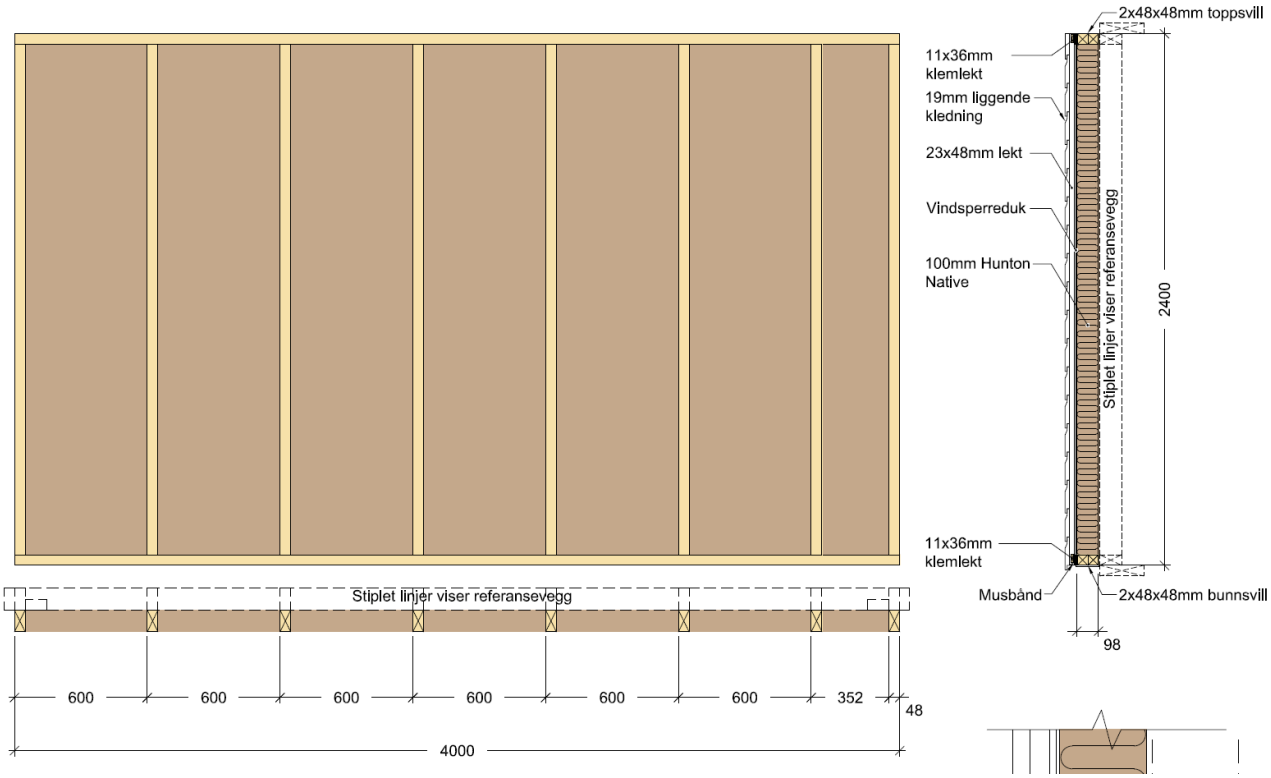


Figure 9. Technical drawing of the renovation scenario B.

Table 5. Materials bought for renovation scenario B.

Material	Total amount	Unit
Timber 48x48 mm	16.8	m
Timber 48x98 mm	19.2	m
Hunton Nativo 100 mm	10	m^2
Wind barrier	10	m^2
Timber 23x48 mm	19.2	m
Timber 11x36 mm	8.4	m
Mouse barrier	4.2	m
Wood cladding 19x149 mm	79.7	m
Screws 6x180 mm	1	bag
Screws 4,4x52 mm	1	bag

3.3.1 Lab set-up description

To ensure the evaluation form was meaningfully capturing relevant information for the assembly and disassembly process with respect to the evaluation criteria set (see beginning of section 3.2), a video-recording set-up was devised to complement the data collection of the evaluation form for the assessment of the SINTEF LAB wall mock-up. Professional-grade cinema cameras were used for video recording, to ensure recording over several hours of operation. The first camera was placed above the construction site with a 21mm lens for capturing the overall construction area and the worker movement between the wall and the working stations. A second camera with a 50mm lens was placed on a wheel cart for following closely and in detail the worker operations. Shotgun microphones were used to synchronize the video recordings for data analysis. Videos were recorded at 30 frame/second at 1080p resolution (Full HD) to ensure portability of the video file and enough information for capturing the worker's movements. Video files were automatically stored on external HDDs connected to the cameras.



Figure 10. Camera set-up.

The lab test was arranged in such a way the operator had easy access to tools and materials, given the space availability in the lab premises (Figure 12). The tools used more frequently such as screwdrivers and the technical drawings were placed in a station at circa 4 m from the test wall. Two deposits of materials (in Figure 12) were set for the insulation materials and wind barrier, and a deposit and cutting station were set for the timber elements and cladding (not visible in figure). All stations and material deposits were placed at less than 10 m from the test wall.

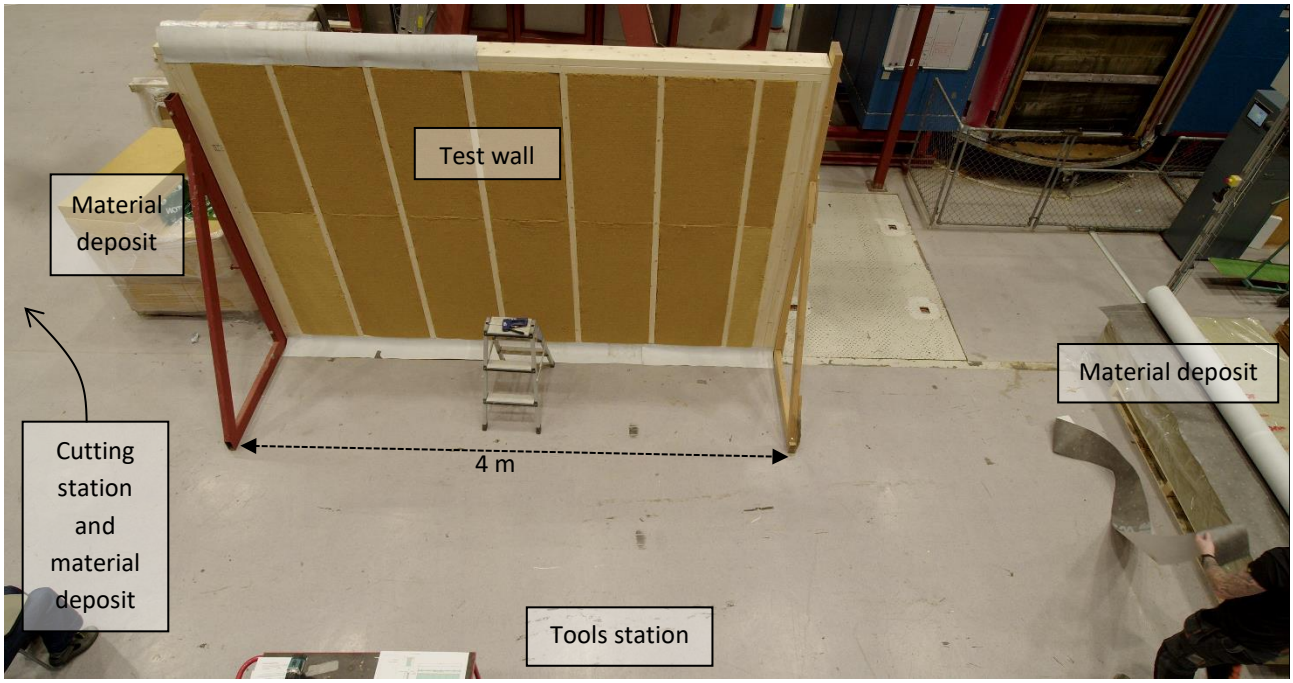


Figure 11. Set-up of the test wall and working stations.

3.3.2 Assembly: overall elapsed time

A preliminary assessment of the assembly and disassembly procedures of both renovation scenarios A and B covered the following aspects:

- Overall time for assembly and disassembly of each renovation scenario (estimated through the assessment form)
- Difficulty at performing assembly and disassembly tasks by the operator (evaluated during an interview)
- Amount of damaged and wasted elements during the assembly and disassembly procedures.

The time assessment was carried out by calculating the time the operator was either working on the test wall, or working at one of the stations, or thinking and studying the technical drawings, or collecting materials, or walking between the stations and the wall. The time the operator was idle in pauses was not calculated. Further on, detailed analysis of the whole construction process was carried out by using the video recording to get a better understanding of the time-performance of the operator for each of the actions and tasks (e.g. cutting, fixing, etc) in relation to the difficulties described in the interview. The assembly and disassembly procedures of both renovation scenarios were as follows:

1. Assembly of renovation scenario A (until step 8, Table 6)
2. Disassembly of renovation scenario A (until step 2, Table 6)
3. Assembly of renovation scenario B (until step 4, Table 7)
4. Disassembly of renovation scenario B (until bare reference wall)

A complete assembly a disassembly process of both scenarios was not carried out because some steps were identical between the two, and therefore it was decided to carry out the work for those steps that showed differences between the two insulation systems. The time elapsed for the steps 1,2 and 5 to 8 are therefore identical between the two renovation scenarios.

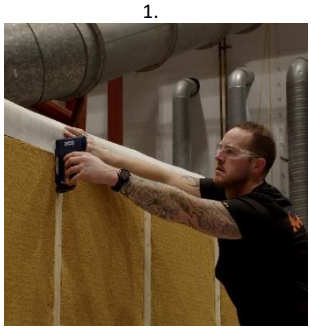
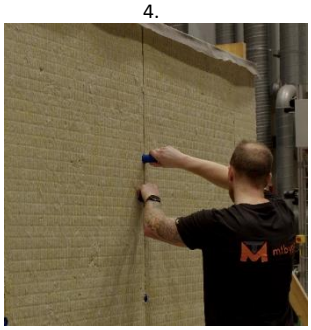
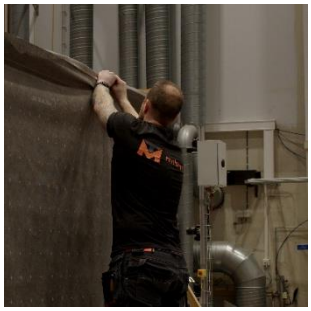
The carpenter hired to perform the assembly and disassembly of the renovation scenarios A and B was interviewed after the completion of each of the construction procedures. Given the task of maximizing the disassembly operations, he decided to use screws for fixing the timber elements and the cladding, whereas this is normally done by using a nail-gun. According to the carpenter, differently from the "standard" procedure of using a nail-gun, the use of a powered screwdriver takes a larger amount of time, but it ensures highest reusability of the construction elements. Based on the carpenter past experience, disassembly has been made easier by the replacement of flat head or star head screws with Torx, since these last are less damaged during the disassembly, and the elements can be reclaimed more easily. According to the carpenter, clients ask more often than before to reuse cladding, and as a result, its installation is done more frequently with screws. Moreover, construction companies often reuse insulation panels and matts when their performance is considered satisfactory by visual inspection and age of the products.

Renovation scenario A.

The renovation scenario A was carried out in 8 steps, as follows: 1. installation of wind-barrier protection on the top and bottom joists of the reference wall, 2. installation of the top and bottom joists of the wall construction A, 3. installation of the insulation panels, 4. fixing of the insulation panels with the plastic spacers and screws, 5. installation of the wind-barrier, 6. installation of the timber frame for supporting the cladding, 7. installation of the rodent mesh protection, 8. installation of the cladding. The overall assembly took 2 hours and 42 minutes.

As shown in Table 6, the time needed to install the insulation (including all the preceding steps 1 to 4) took approximately 36 minutes. According to the carpenter, he did not have previous experience with this type of insulation, therefore extra time for studying the installation procedure was needed, especially at step 4. Since the large format (270 cm by 120 cm) of these insulation boards, the carpenter considered this aspect advantageous on large walls with few "details" (windows, recesses, etc.) because it reduces the installation time and ensures a higher continuity of the insulation layer and lower thermal bridges. Moreover, the system avoids the need of cutting and installing the second timber frame for allocating the insulation board. On the other hand, smaller walls or walls with more details and more complicated geometry benefit from a smaller format of insulation boards to reduce cutting waste. A disadvantage of this system is the need to take extra time for finding the plastic spacers when screwing the second layer of timber elements to support the cladding (step 6). The carpenter said in the interview he needed to be sure not to screw on the plastic spacers but either above or below them.

Table 6. Assembly steps of renovation scenario A and corresponding times expressed in hh:mm:ss.

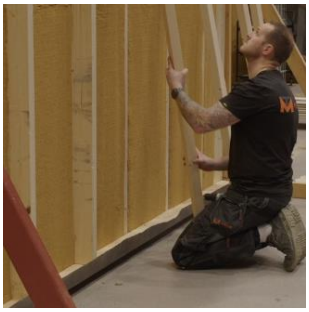
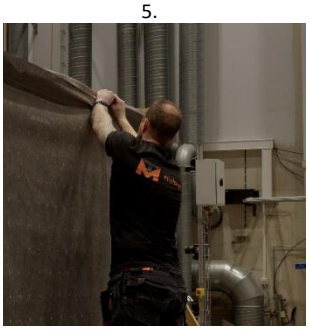
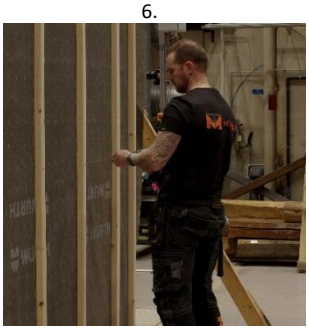
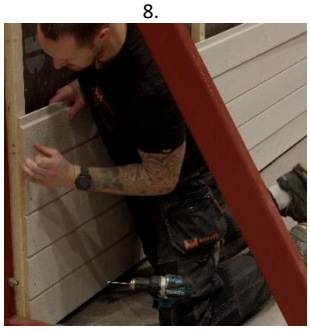
1.	2.	3.	4.
			
00:06:07	00:10:49	00:10:10	00:09:29
5.	**6.**	**7.**	**8.**
			
00:08:35	00:38:19	00:09:47	01:06:29

Renovation scenario B

The renovation scenario B consisted in 8 steps, as follows: 1. installation of wind-barrier protection on the top and bottom joists of the reference wall, 2. installation of the top and bottom joists of the wall construction A, 3. installation of the timber frame, 4. installation of the insulation panels, 5. installation of the wind-barrier, 6. installation of the timber frame for supporting the cladding, 7. installation of the rodent mesh protection, 8. installation of the cladding. The overall assembly took 3 hours.

As shown in Table 7, the time needed to install the insulation (including all the preceding steps 1 to 4) took approximately 55 minutes. According to the carpenter, the insulation panels are relatively rigid, and he needed to apply a more force than usual to get them in place. The advantage of wood fiber panels is their smaller size and easier adaptability to straighten up old and crooked walls in comparison to the insulation system used in the other renovation scenario. The installation process of the insulation (steps 3 and 4) took 18 minutes longer than for the renovation scenario A. This was due to the time needed to cut the frame (step 3) and cut a larger number of panels (14 for renovation scenario B against 4 for the renovation scenario A). The specific installation time was circa 5 minutes per mineral wool panel (steps 3 and 4) and circa 3 minutes per wood fiber panel (steps 3 and 4). As mentioned, the carpenter was well acquainted with the installation procedure of this type of insulation.

Table 7. Assembly steps of renovation scenario B and corresponding times expressed in hh:mm:ss.

1.  00:06:07	2.  00:10:49	3.  00:18:26	4.  00:19:31
5.  00:08:35	6.  00:38:19	7.  00:09:47	8.  01:06:29

3.3.3 Assembly: time performance and waste produced

This section presents a more detailed analysis of the time effort of specific actions taken by the carpenter during the installation of either insulation systems, for steps 3 and 4. The following actions were identified for either of the installation procedures:

- Renovation scenario A: thinking (e.g. studying the technical drawings), cutting the panels, measuring, placing the panel between the joists, walking between the wall and the other working stations, fixing the panels with the insulation spacers).
- Renovation scenario B: thinking, sawing and cutting the timber elements, placing the timber elements, screwing the timber elements on the reference wall, measuring, cutting the insulation panels, placing the insulation panels in the frame, walking between the wall and the working stations.

As shown in Table 8, the most notable difference between the two renovation scenarios is the time for walking from and to the test wall (additional 6 minutes and 31 seconds for the renovation scenario B) and the time for placing the insulation panels (additional 2 minutes and 40 seconds for the renovation scenario B). In contrast, little extra time was needed to saw and screw the timber elements (additional 1 minutes and 38 seconds for scenario B) against the time needed to fix the insulation boards with the spacers (scenario A). In relation to the total time needed for completing steps 3 and 4, the three most time-consuming activities of scenario A were the fixing of the insulation panels with the plastic spacers (35% of total time), followed by cutting (18%) and placing (18%) the insulation panels. In scenario B, the three most time-consuming activities were the placing of the timber element and the insulation panels (27%), walking between the working stations and

the wall (24%), and screwing the timber elements to the reference wall (18%). It can be concluded that a different arrangement of the working stations could reduce the walking time in renovation scenario B, and thus partially compensating for the additional installation time needed.

Table 8. Actions for the two renovation scenarios and their respective times in hh:mm:ss.

Renovation scenario A		hh:mm:ss	Renovation scenario B		hh:mm:ss
step 3	Thinking	00:00:17	step 3	measuring	00:02:36
	measuring	00:00:53		sawing	00:01:47
	cutting	00:03:33		placing	00:04:10
	placing	00:03:27		screwing	00:06:45
	walking	00:02:00		walking	00:03:08
step 4	Thinking	00:00:23	step 4	Thinking	00:01:50
	measuring	00:01:43		measuring	00:00:44
	fixing	00:06:54		placing	00:06:07
	walking	00:00:29		cutting	00:04:58
				walking	00:05:52

Table 9 shows the waste produced during the assembly procedure of both scenarios, and the main materials used during step 3 and step 4. The waste from the materials used in the other steps is not evaluated here since there were not any noteworthy differences between the two scenarios. The *Used* heading refers to the share of the total material bought, *Cuts* refers to the amount of material cut with respect to the amount used, *Not used* refers to the not used material and it is calculated by subtracting material *Used* from material bought, *Non-reusable share of cuts* is calculated by considering the amount of *Cuts* which is non reusable with respect to the original standard dimension of each element. Specifically, for the mineral wool panel, a reusable cut was considered when its total length equals the height of the reference wall, whereas a reusable cut of wood-fiber panel must have a width of 60 cm at least. Given the larger size of the mineral wool panels (scenario A), a larger share of cuts and waste (non-reusable share of cuts) was recorded at the end of the assembly procedure, in contrast to the use of wood fiber panels (scenario B). The plastic spacers did not produce waste, whereas 4% of the used timber elements were wasted. Overall, scenario B (0.04 m^2) produced less waste than scenario A (0.46 m^2), and it can be concluded that this was the main drawback of the use of larger panels, in contrast to the produced benefit of reducing the installation time, as seen in the previous section.

Table 9. Material used and waste produced for steps 3 and 4.

		Used	Cuts	Not used	Non-reusable share of cuts
Scenario A	Insulation panels	63%	59%	0%	27%
	Insulation spacers	60%	0%	40%	0%
Scenario B	Insulation panels	91%	10%	9%	3%
	Timber 48x98mm	85%	4%	15%	100%

3.3.4 Disassembly: time performance, waste and damaged elements

Table 10 shows the corresponding times of the disassembly steps for the removal of the cladding (1), rodent mesh (2), wood frame (3), and wind barrier (4) taken in both renovation scenarios. As mentioned above, the assembly and disassembly of the finishing layer and wind barrier were carried out only once since the procedure was identical in both renovation scenarios. To maximize the material reusability, the carpenter was asked to use screws instead of nails whenever possible. The overall disassembly time for the finishing and wind barrier (steps 1 to 4) took 23 minutes, of which half was used for removing the cladding.

Table 10. Disassembly steps of renovation scenarios A and B and corresponding times expressed in hh:mm:ss.

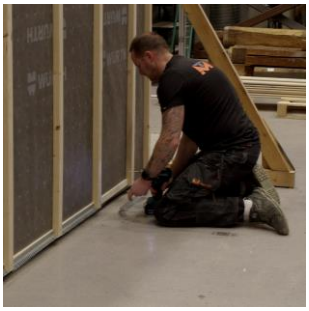
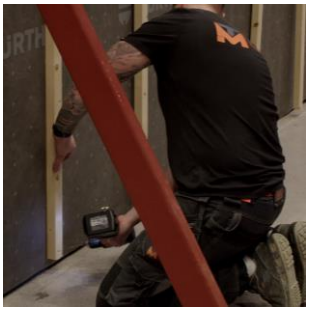
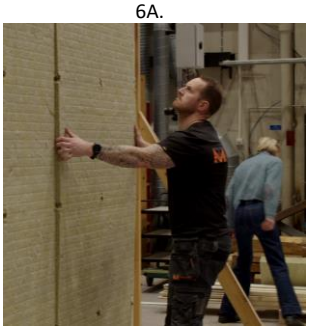
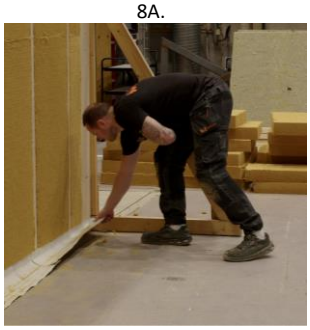
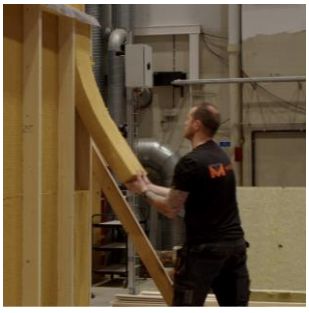
1.	2.	3.	4.
			
00:12:42	00:01:21	00:07:11	00:02:14

Table 11 shows a comparison of the disassembly steps of the insulation and supporting layers between scenarios A and B. The overall time for removing the mineral wool and supporting layers (steps from 5A to 8A) was 8 minutes, against almost 12 minutes for the same steps in Scenario B. The main difference was due to the unscrewing of the timber frame (step 6B) needed to hold the wood-fiber panels, whereas the time needed to remove corresponding support system for the mineral wool panels (step 5A) was shorter. From step 5 to 8, in both scenarios, the main actions taken by the carpenter were the removal of material from the wall, the removal of screws (with an electric screwdriver) and of the insulation spacers (by hand, in scenario A), and the movement from and to the wall to set the material aside. In scenario A, the removing action took most of the elapsed time (42%), especially for the insulation spacers (step 5A), whereas in scenario B, the most time-consuming action was the unscrewing (50% of the elapsed time), equally divided between steps 6B and 7B. In contrast to the installation time, the overall disassembly of the wall construction took between 31 minutes (scenario A) and 35 minutes (scenario B). A comparative assessment of assembly and disassembly between the use of screws and nails was not carried out, so it is not possible to evaluate the benefit of reusing the materials (especially cladding) against the additional time effort needed for the operations. However, given the disassembly time was circa 1/5 of the assembly time in both scenarios, it can be concluded that the benefit of potentially reusing the building elements of these types of constructions surpasses the drawbacks of additional time efforts. With respect to reusability of the two types of insulation used, 90% of mineral wool panels and 92% of wood fiber panels were deemed reusable. Their reusability was assessed by considering

those disassembled panels that were still fitting a similar construction. Specifically, the wood-fiber panels sizing 600 mm by 1200 mm and the mineral wool panels sizing 1200 mm by 2400 mm were considered reusable (see constructions dimensions of Scenario A and B in Figures 10 and 11, respectively). Disassembled cladding and wood members were deemed 100% reusable, due to the use of screws, and the plastic spacers used in Scenario A as well. The wind barrier and the rodent mesh were considered as waste.

Table 11. Disassembly steps of renovation scenarios A and B and corresponding times expressed in hh:mm:ss.

5A.	6A.	7A.	8A.
			
00:01:41	00:01:59	00:03:50	00:00:31
5B.	6B.	7B.	8B.
			
00:02:46	00:04:44	00:03:48	00:00:30

Description of case studies

The following section describes briefly the case studies and the tests performed in the laboratory of the University of Stuttgart (USTUTT), and in the outdoor facilities of CEA and SINTEF. A detailed description of the construction mock-ups and tests is provided in deliverable D4.2.

3.4.1 USTUTT LAB mock-up

The construction mock-up built at the laboratory of the Materials Testing Institute University of Stuttgart consists of four wall assemblies with variations of types of brick and renders, as described

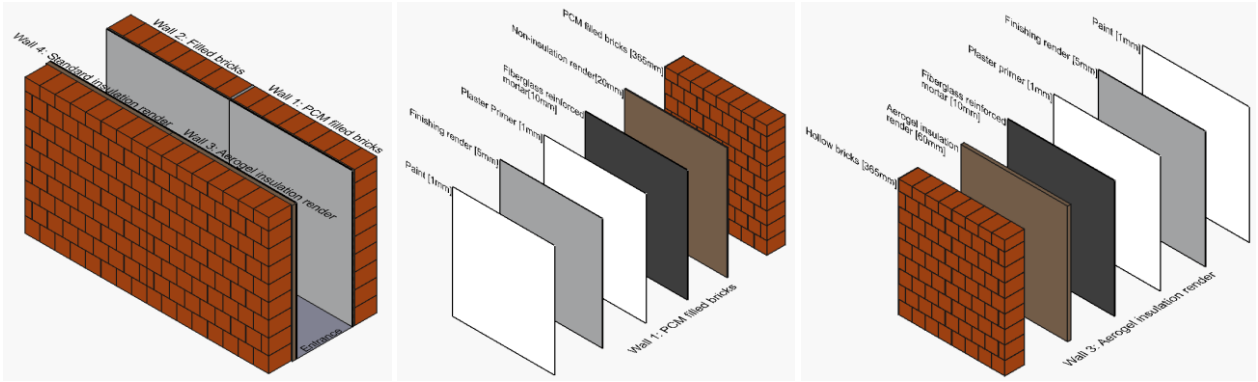


Figure 12. Left: schematic of the arrangement of the four wall assemblies. Right: schematic of the layers composing two of the wall constructions.

in Table 12 and shown in Figure 13.

Table 12. Description of the layers of the four wall constructions

	Wall 1	**Wall 2**	**Wall 3**	**Wall 4**
Indoor	PCM-filled bricks	Insulated bricks	Hollow bricks	Hollow bricks
	Perimeter insulation board frame 20 mm	Perimeter insulation board frame 20 mm	Perimeter insulation board frame 60 mm	Perimeter insulation board frame 60 mm
	Non-insulated render 20 mm	Non-insulated render 20 mm	Aerogel-insulated render 60 mm	Standard insulated render 60 mm
	Adhesive reinforced mortar	Adhesive reinforced mortar	Adhesive reinforced mortar	Adhesive reinforced mortar
↓	Fiberglass mesh	Fiberglass mesh	Fiberglass mesh	Fiberglass mesh
	Fiberglass-reinforced edge	Fiberglass-reinforced edge	Fiberglass-reinforced edge	Fiberglass-reinforced edge
	Plaster primer	Plaster primer	Plaster primer	Plaster primer
	Finishing plaster	Finishing plaster	Finishing plaster	Finishing plaster
Outdoor	Paint	Paint	Paint	Paint

The construction was performed by professional construction workers. The data collection of the construction process (assembly and disassembly) consisted of filling the assembly and disassembly forms, provided by SINTEF, and filming the assembly and disassembly procedures with three cameras, positioned to show the construction process from different angles and make sure almost all the workers' activities were visible. The videos were used to carry out a detailed analysis of the brick layering process to measure the performance of bricks with PCM filling, developed in EZ0 as

an innovative product. The video analysis was done to evaluate and compare the performance of three types of bricks (PCM-filled bricks, insulated bricks, and hollow bricks, as detailed in Table 12) during the brick layering process with respect to the elapsed time of the different operations and workers' actions. The hypothesis at the basis of this analysis is whether the hollow bricks (used in wall 3 and wall 4), the insulated and heavier bricks (used in wall 1 and wall 2) take more time to be layered and if the operation is experienced fatiguing and difficult by the operators. The videos were analyzed in professional video editing software (Davinci Resolve studio), the video timeline split according to the main operations of the brick layering process and further split according to the main workers' actions. The following operations were identified (as shown in Figure 14):

- Bricks layering, consisting of the actions of taking the bricks from the pallet, carrying them by the wall, placing them on the wall, adjusting their position.
- Cement layering, consisting of layering cement mortar between brick layers.
- Bricks unloading and unpacking, consisting of carrying pallets of bricks by the working area and removing the protective plastic wrap.
- Cement preparation, consisting of mixing the cement bags with water and carrying the mortar to the working area.
- Idle time, consisting of resting time or waiting time for the cement mortar to dry.



Figure 13. Main operations carried out for the construction of the four brick walls

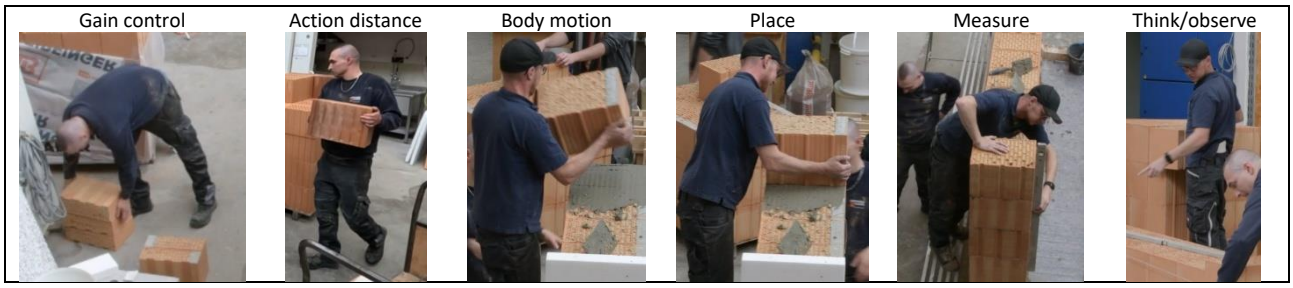


Figure 14. Main actions (based on the MOST sequence) carried out during the brick layering operation.

During the brick layering operation three workers with different proficiencies were operating; a professional, a trainee, and an aide.

The following workers' actions (based on the basic MOST sequence) were identified during the brick layering operation (as shown in Figure 15):

- Action distance, consisting of horizontal walking movements of the workers, when carrying bricks to the wall and returning to the pallet.
- Body motion, consisting of body movements (without walking) of the workers when handing over brick to each other and taking bricks from the pallet.
- Gain control, consisting of the action of taking hold of the brick preceding the body motion.
- Place, consisting of the action of placing and aligning the brick on the wall, with and without tools (hammer).
- Measure, consisting of measuring the alignment of bricks.
- Think and or observe, consisting of counting the bricks and assessing the right alignment after measuring.

Finally, the analysis of the elapsed time to reclaim the bricks was analysed by considering the bricks that could be salvaged with respect to the total bricks disassembled.

3.4.2 CEA Test facility

CEA test facility consists of two outdoor constructions where building products can be installed and tested in outdoor weather conditions. The renovation strategy consisted of spraying 100 mm of bio-PUR insulation on the existing internal gypsum board and finishing the wall with gypsum boards. This solution increased the wall insulation, calculated from 0.94 W/m^{2}K for the pre-renovated wall to 0.24 W/m^{2}K.

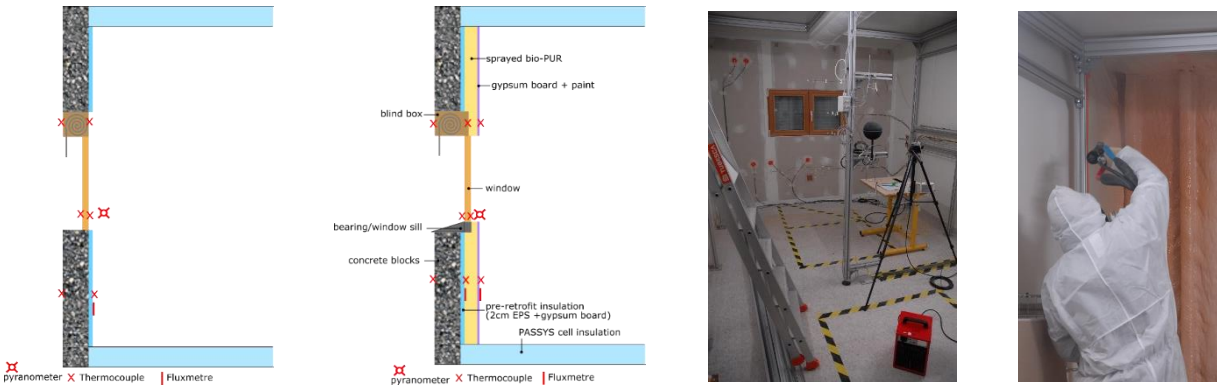


Figure 15. Left: Wall section of test cell before and after renovation. Right: view of the test cell and spraying of bio-PUR insulation-

Table 13. Description of the layers composing the wall construction tested by CEA

Before renovation		**After renovation**	
Material	Thickness	Material	Thickness
Ext. coating	20 mm	Ext. coating	20 mm
Hollow concrete blocks	200 mm	Hollow concrete blocks	200 mm
EPS	20 mm	EPS	20 mm
Gypsum board	13 mm	Gypsum board	13 mm

Old window + blind box	-	Bio-PUR foam	100 mm
		Gypsum board	13 mm
		Bio-PUR window + wooden blind box	-

The analysis of the construction process was carried out by filling in the assembly forms provided by SINTEF, described in section 3.2. Information regarding time for assembly of each layer, waste produced, and difficulty of operation was recorded.

3.4.3 SINTEF Test facility

SINTEF test facility consists of an outdoor construction consisting of two identical cells. The external façade of each cell is removable and building products can be installed and tested in outdoor weather conditions.

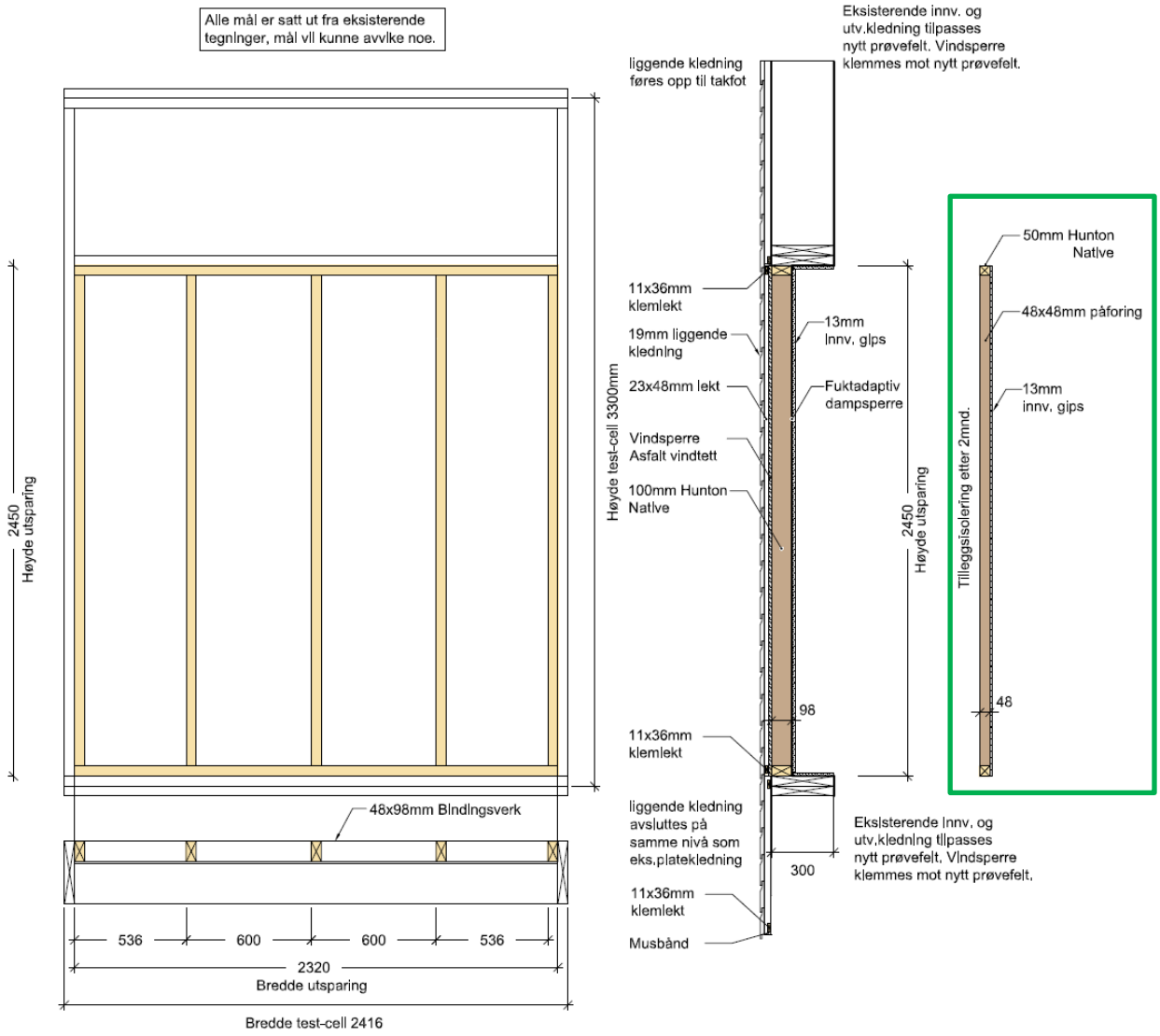


Figure 16. Scheme of the wooden frame construction tested by SINTEF. Highlighted in green the additional layers installed in the renovation process.

The wall construction tested by SINTEF replicated a wall built in the period 1950-1969, as detailed in section 3.3. Differently from the renovation test performed in the SINTEF laboratory (see in section 3.3), the additional insulation (50 mm wood fiber panels) was added to the interior of the existing construction. The thickness of the new insulation layer was 50 mm to limit the reduction of available floor area while ensuring higher insulation (calculated from 0.35 W/m^{2}K for the pre-renovated wall to 0.23 W/m^{2}K).

Table 14. Description of the layers composing the wall construction tested by SINTEF

Before renovation		**After renovation**	
Material	Thickness	Material	Thickness
Exterior cladding	19 mm	Exterior cladding	19 mm
Wooden battens	23 mm	Wooden battens	23 mm
Wind barrier	12 mm	Wind barrier	12 mm
Wood fiber insulation	100 mm	Wood fiber insulation	100 mm
Vapor barrier	0.15 mm	Wood fiber insulation	50 mm
Gypsum panels	13 mm	Vapor barrier	0.15 mm
		Gypsum panels	13 mm

Table 15. Disassembly and assembly operations, SINTEF test facility.

Disassembly			
1. Window jamb, head, and sill	2. Gypsum panels		
			
Assembly			
3. Wood battens	4. Wood fiber panels	5. Gypsum panels	6. Window jamb, head, and sill
			

During the renovation procedure, video recordings were taken and information regarding time for assembly of each layer, waste produced, and difficulty of operation was recorded. The video recording was used to identify the main operations and their corresponding elapsed times during the disassembly of the interior gypsum finishing, and the assembly of the additional insulation and placing back the gypsum finishing, as shown in Table 15. The operation was carried out by a skilled SINTEF laboratory technician, aided by a researcher during some of the operations.

4. Results

USTUTT LAB mock-up

This section presents the results of the overall wall constructions time and waste provided in the assembly and disassembly assessment forms. In addition, results of the brick layering process are obtained from the video analysis.

4.1

4.1.1 Assembly

The amounts of materials and description of the layers of each of the 4 wall constructions is given in Table 16

Table 16. Weights and assembly waste for each layer.

Wall 1	Used	Waste	Wall 2	Used	Waste
PCM-filled bricks	1018 kg	0%	Insulated bricks	996 kg	0%
Perimeter insulation board 2 cm	0.45 kg	2.2%	Perimeter insulation board 2 cm	0.45 kg	2.2%
Non-insulated render	39 kg	49%	Non-insulated render	39 kg	49%
Adhesive reinforced mortar	10 kg	0%	Adhesive reinforced mortar	10 kg	0%
Fiberglass mesh	4 kg	6.3%	Fiberglass mesh	4 kg	6.3%
Fiberglass-reinforced edge	3 kg	13.3%	Fiberglass-reinforced edge	3 kg	13.3%
Plaster primer	2.5 kg	0%	Plaster primer	2.5 kg	0%
Finishing plaster	12.5 kg	4%	Finishing plaster	12.5 kg	4%
Paint	2 kg	0%	Paint	2 kg	0%
Wall 3	**Used**	**Waste**	**Wall 4**	**Used**	**Waste**
Hollow bricks	984 kg	0%	Hollow bricks	984 kg	0%
Perimeter insulation board 6 cm	1.75 kg	6.3%	Perimeter insulation board 6 cm	1.75 kg	6.3%
Aerogel-insulated render	40 kg	24.1%	Standard insulated render	37.6 kg	23%
Adhesive reinforced mortar	10 kg	0%	Adhesive reinforced mortar	10 kg	0%
Fiberglass mesh	4 kg	6.3%	Fiberglass mesh	4 kg	6.3%
Fiberglass-reinforced edge	3 kg	13.3%	Fiberglass-reinforced edge	3 kg	13.3%
Plaster primer	2.5 kg	0%	Plaster primer	2.5 kg	0%
Finishing plaster	12.5 kg	4%	Finishing plaster	12.5 kg	4%
Paint	2 kg	0%	Paint	2 kg	0%

The preparatory steps for the assembly of the 4 walls were the following:

- **Preparation in advance**: The EOTA wall test rig was prepared by extending the base area for the expected wide bricks using stable wood formworks. The bricks and the respective mortar were delivered in advance and stored for multiple days indoor dry indoor, about at a 20-meters walking distance. Renders and plaster were delivered by the personnel on the day of application. Plaster primer and paint were delivered in advance and stored indoors, nearby the installation site.
- **Bricklaying**: Moving the previously delivered bricks from one hall compartment to the site; Tools (different trowels, levels, guiding rails, buckets, stirring machine, application aid 'Unimax 36.5') and mortar (capping thin-bed mortar, leveling supplementary mortar) were loaded off the car; Half bricks (used later as beginning/end brick in every second brick row) were sorted out first;
- **Render application**: The application machine was loaded off the car and prepared for usage; frames (made from Styrofoam) around the edges of the walls were applied for easier leveling

on the small plane walls; tools (trowels, levels, buckets, stirring machine) and materials (separation tape, render) were unloaded from car.

- **Fabric reinforced mortar application**: Materials (adhesive reinforcing mortar, fiberglass mesh) & tools (trowels, stirring machine) were unloaded from the car.
- **Plaster primer application**: The plaster primer (mixed with quartz sand) was delivered and stirred; tools (paint rollers, brush, scraping grid) were prepared.
- **Finishing plaster**: Material (plaster) and tools (trowels, buckets, stirring machine) unwere loaded.
- **Paint**: The paint was stirred, tools were already present from the plaster primer

The assembly operations of wall constructions are summarized in general steps in the list below. Small variations of operations carried out in the wall constrictions are not described here:

- **Bricklaying**: First, the base area of the brick wall was leveled out using the leveling supplementary mortar and the guiding rails. The first row of bricks was set into this bed of mortar after an appropriate amount of waiting time. Each next row of bricks was laid by applying the thin-bed mortar first and setting each brick in place, using a level to create a perpendicular wall.
- **Render**: The render was filled into the application machine and applied under air pressure from the nozzle. The applied render was then leveled out to create an approximately even wall area.
- **Fabric reinforced mortar**: The mortar was stirred manually with an appropriate machine. One layer of mortar was applied, onto which a fiberglass mesh was set in long, vertical strips, ensuring that each strip overlaps at least 10cm to the next to prevent cracks from forming. Another layer of mortar was applied and leveled out.
- **Plaster primer**: The stirred plaster primer was applied using typical painting tools in a single layer onto the walls. This is to ensure better grip for the finishing plaster as well as evenly drying behavior.
- **Finishing plaster**: The plaster was stirred and applied by hand directly onto the surface. After a short waiting period, it was structured using a plastic trowel and moving it with low pressure in a circular motion over the plaster.
- **Paint**: The dried plaster was painted twice with 3 days of drying in between. The paint was diluted with 5% of water (as per manufacturer's recommendation) and applied using typical painting tools

The elapsed time for the assembly of each layer of the four wall constructions were recorded in the assembly assessment form, and results are given in Table 17

Table 17. Elapsed time for each layer.

Wall 1 (from outside to inside)	Time (hh:mm:ss)	Wall 2 (from outside to inside)	Time (hh:mm:ss)
Outside paint	00:13:00	Outside paint	00:13:00
Finishing plaster	00:18:00	Finishing plaster	00:18:00
Plaster primer	00:07:00	Plaster primer	00:07:00
Fiberglass-reinforced mortar	00:42:00	Fiberglass-reinforced mortar	00:42:00
Fiberglass mesh		Fiberglass mesh	
Non-insulated render	00:32:00	Non-insulated render	00:32:00
PCM-filled bricks	01:26:00	Insulated bricks	01:36:00
Adhesive reinforced mortar		Adhesive reinforced mortar	
Wall 3 (from outside to inside)	**Time (hh:mm:ss)**	**Wall 4 (from outside to inside)**	**Time (hh:mm:ss)**
Outside paint	00:17:00	Outside paint	00:17:00
Finishing plaster	00:14:00	Finishing plaster	00:14:00
Plaster primer	00:10:00	Plaster primer	00:10:00
Fiberglass-reinforced mortar	00:40:00	Fiberglass-reinforced mortar	00:40:00
Fiberglass mesh		Fiberglass mesh	
Aerogel-insulated render	01:44:00	Insulated render	01:59:00
Hollow bricks	01:15:00	Hollow bricks	01:15:00
Adhesive reinforced mortar		Adhesive reinforced mortar	

The operation of layering the PCM-filled bricks (Wall 1) required some extra steps by the operator. This was due to the use of a thin-bed mortar which filled the hollow chambers of the bricks in the first two rows. The bricks accumulated a slight tilt over the whole height of the wall, resulting in a need to set the top rows about 3mm back to compensate for that. As per the operators' experience, the assembly operation was of average difficulty and easiness to access and work in the wall layers. The assembly operations of the other three wall constructions were carried out without extra effort and were rated as average difficult by the operators. Most notable differences were the 10-minutes shorter time for the installation of the PCM-insulated bricks (Wall 1) with respect to the regular insulated bricks (Wall 2), which resulted in a 10% shorter installation time of the brick layer. On the other hand, the installation of the hollow bricks (Walls 3 and 4) was 10 minutes shorter than that of the PCM-insulated bricks (Wall 1) and 20 minutes shorter than that of the insulated bricks (Wall 2). The recorded time for brick layering included the activity of layering the mortar. A more detailed analysis of the brick layering process, presented below, included the brick layering process only (of which the main MOST actions are described in Figure 15). The overall elapsed time for the brick layering process was circa 29 minutes for Walls 1 and 2, and circa 30 minutes for Walls 3 and 4.
A detailed analysis was carried out on the average time for the operators' action of Gain Control and Place of the bricks. The hypothesis behind this analysis was to evaluate to what extent the difference in weight between the insulated bricks (either with or without PCM) and the non-insulated bricks required an extra effort for the installation process. Gain Control and Place were identified as those two actions to be more affected by the difference of brick weight.

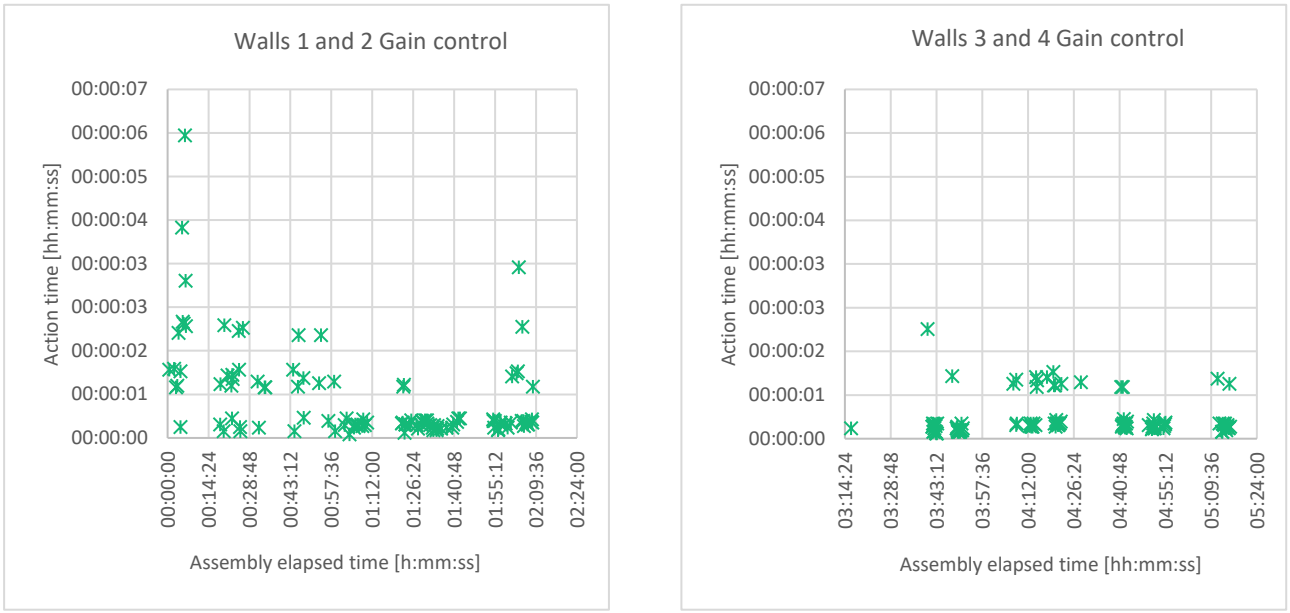


Figure 17. Action times for Gain Control of bricks.

Figure 18 shows the time needed to perform each Gain Control action during the installation of the brick layers in Walls 1 and 2 (left) and Walls 3 and 4 (right). The average time for Gain Control for the insulated bricks (either with or without PCM) was 1 second, whereas it was ½ second for the hollow bricks. Figure 18 left shows that after the first hour of installation the operators found a faster way for taking hold of the bricks, with an average time lower than 1 second, similar to the time needed for the hollow bricks.

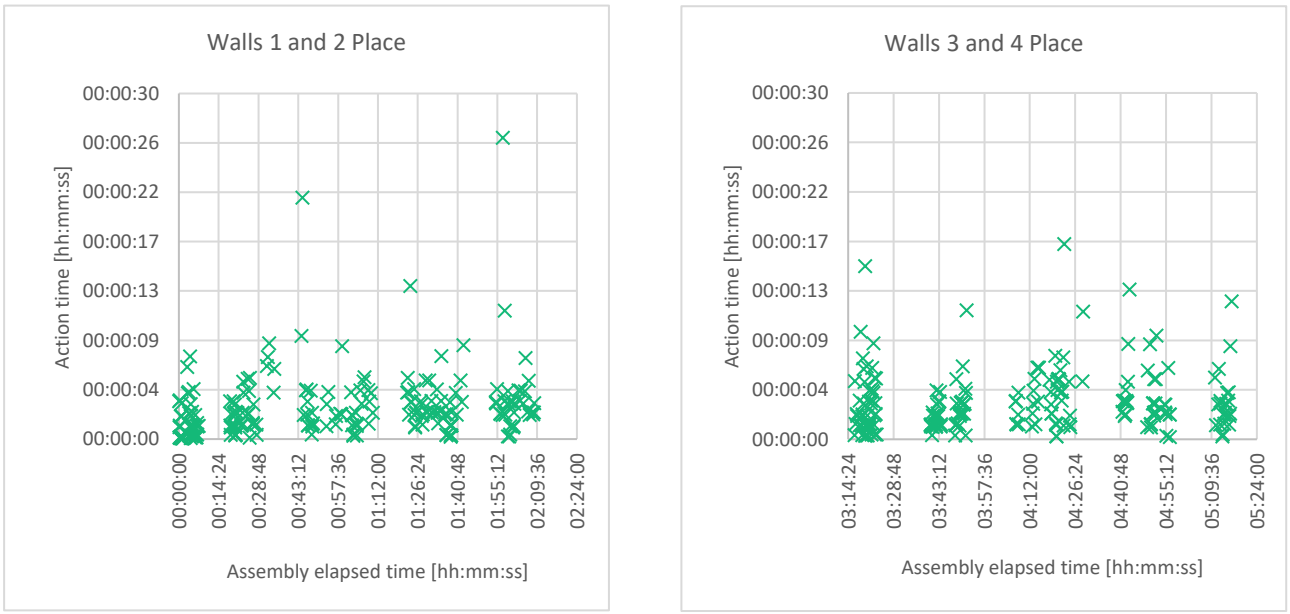


Figure 18. Action times for Place of bricks.

Figure 19 shows the time needed for performing the Place action. The average time for placing the bricks was 5 seconds in Walls 1 and 2, and 6 seconds in Walls 3 and 4. The extra 1 second per brick was due to the need of using the hammer to tighten the hollow bricks to their position, operation that was not needed for the insulated bricks of Wall 1 and 2. For this reason the average placing time for the insulated bricks was more consistent (and under 5 seconds) than that of the hollow bricks. The two most time-consuming actions were Place (circa 35% of the whole time for the brick layering process) and Body Motion (circa 37%). The elapsed time for the Place action carried out in Walls 1 and 2 was 14% shorter than that in Walls 3 and 4. Conversely, the elapsed time for Body Motion carried out in Walls 1 and 2 was 11% longer than that in Walls 3 and 4. Therefore, it cannot be concluded that the difference of weight between the hollow and filled bricks led to a significant difference of overall assembly time.

4.1.2 Disassembly

During the disassembly of the wall constructions the operators were asked to maximize the recovery of the bricks, by carefully separating the mortar, paint, and plaster from the bricks. The salvaged bricks were then stored apart and counted. The operation was evaluated as difficult and time consuming. The following details were the main challenges of the disassembly operations.

Wall 1

For most elements of the wall (paint, plaster, plaster primer, fabric-reinforced mortar, non-insulating render), reusability was hardly possible, if at all. Therefore, disassembled wall segments were destroyed and put into a recycling container to be removed by a recycling company. Due to high effort required to retrieve elements, it was decided that only 2 rows of the bricks themselves would be attempted to be retrieved. The retrieved bricks still had mortar on the top and bottom sides (not easily removable) as well as residual render on the front sides (easy to remove). It was assumed that the same rate of retrieval would be realistic for the remaining 6 rows of bricks. The remaining materials could not be reused in their current state. Disassembling the wall in a way that provides the possibility of reusability made the process very arduous and laborious. Nevertheless, several bricks were recovered for a potential reuse and most importantly by keeping the PCM-filled chambers intact. The mortar used to connect the bricks to each other could not be easily removed without an unreasonable effort. This resulted in a higher height of the bricks, 8.2mm on average. Reusing those bricks would require a much thicker mortar bed, which would result in much higher mortar use and therefore make it possibly not economically feasible. The process of removing the bricks was regularly strenuous and resulted in uncomfortable positions. This led to disposing as waste 13% of the total mass of the bricks for which recovery was attempted.

Wall 3

The Aerogel-insulation render was easy to remove from the brick surface with low residues left on the brick's surfaces. Collecting the render after scraping it off and packing it into nearly pure packages of render would indeed be possible, but the economic aspect of such time-consuming process was not evaluated. Besides the exhausting work required to disassemble the wall, both workers experienced limited skin irritations (known side effects of working with silica-based aerogel)

on the arms and necks (most likely from dust development in the air) in the evening of the same day, lasting for a few days. Those irritations vanished by themselves, leaving no permanent marks.

CEA Test facility

This section presents the results of the overall wall constructions time and waste provided in the assembly assessment forms. The overall assembly procedure took circa 9 hours, carried out by 6 operators of which 2 only were working at any given time.

4.2

4.2.1 Assembly

The assembly steps taken to install the EZ0 products in the CEA test facility were the following:

- Installing timber studs on the existing construction.
- Inserting blind box.
- Spraying BioPUR foam between the timber studs.
- Installing the window.
- Remove the foam excess.

The overall operation was evaluated as easy by the operators with the exception of the following:

- The dimension of the opening to allocate the blind box was too small, and this led to extra time for its installation.
- The process for removing BIO-PUR foam excess was time consuming and needs to be improved by using better tools. A possible solution could be the installation of a frame on top of the wooden studs to support the finishing gypsum board to leave an air gap between the gypsum board and the sprayed BIO-PUR insulation. This solution would make the process of removing all the insulation excess down to the timber stud surface unnecessary and reduce the thermal bridge between the internal gypsum board and the insulation layer.

Table 18. Details of the assembly process at the CEA test facility.

Wall layers (from outside to inside)	Tools used	Elapsed time (hh:mm:ss)	Waste (% of installed mass)	Notes
Concrete blocks (existing)			2%	Waste to make space for the blind box
EPS + gypsum board (existing)			2%	Waste to make space for the blind box
Timber studs	Electric screwdriver	06:00:00	15%	
Tape		00:30:00		
BIO-PUR insulation	Spray machine for application, cutter to remove excess	04:05:00	30%	00:15:00 preparation 00:50:00 spraying 03:00:00 removing excess Waste includes the prepared foam that was not used
Wooden blind box		02:00:00	0%	
Window	Electric screwdriver and PUR foam gun	00:45:00	0%	Installed by manufacturer's operator
Gypsum board	Electric screwdriver			Not part of the assessment
Paint	Brush			Not part of the assessment

Table 18 details the layers and the analyzed parameter during the assembly procedure. Additional comments regarding the difficulty of the operation are given below:

- **Timber studs**. It was difficult to screw the timber studs to the concrete blocks, and it was complicated to obtain a planar surface on the timber studs to easily support the internal finishing (gypsum board)
- **BIO-PUR foam**. Temperature of the foam is a crucial parameter in order to obtain a uniformly thick insulation layer. This led to a time-consuming procedure to remove excess foam that hindered the installation of the gypsum board.
- **Blind box**. The opening in the existing wall was too small and made the installation process more complex.

SINTEF Test facility

4.3 The simulation of the renovation process carried out at SINTEF test facility consisted of first removing the interior gypsum panels and then installing a timber framework to allocate the additional wood-fiber insulation and finally place back the gypsum panels. Steps are described in Table 15.

Table 19. Details of renovation process of test wall, SINTEF test facility

Disassembly				
Wall layers (from inside to outside)	**Tools used**	**Elapsed time (hh:mm:ss)**	**Waste (% of installed mass)**	**Notes**
Window jamb, head, and sill	Electric screwdriver	00:09:00	0%	
Gypsum panels	Electric screwdriver	00:11:15	0%	
Assembly				
Wall layers (from inside to outside)	**Tools used**	**Elapsed time (hh:mm:ss)**	**Waste (% of installed mass)**	**Notes**
Wood battens	Circular saw and electric screwdrivers	00:21:00	15%	
Wood-fiber panels	Band saw, cutter	00:20:45	9%	Thickness of panels was halved by cutting them to reach the 50mm required thickness. Side panels were cut to fit in the wooden posts.
Gypsum panels	Electric screwdriver	00:18:30	0%	
Window jamb, head, and sill	Cutter, Electric screwdriver	00:11:15	0%	

Table 19 describes the elapsed times and waste produced during the disassembly and assembly procedures. The whole disassembly procedure took circa 19 minutes, and the assembly procedure took 1 hour and 5 minutes of which circa 15 minutes were used to cut the wood frame and the wood-fiber panels. The overall procedure was considered easy by the operator.

5. Conclusions

Several tests were conducted in 4 different facilities on the assembly and disassembly procedures of EZ0 products. As per Objective 4 of EZ0 (easy, fast and reliable installation of panels, accessories

and finishing materials) a KPI was identified with the target of reducing the installation time by 30%, to be verified by measurement at lab scale relative to standard renovation process. A comparative assessment between standard products and EZ0 products was carried out in the USTUTT lab test, where hollow bricks were compared against insulated bricks (either with or without PCM). The time-action analysis showed that the installation of the insulated bricks (not including the mortar layering) was 3% shorter than that of the uninsulated bricks. This was due to a faster procedure for setting in place the bricks on the wall. The additional weight of the bricks did not significantly slow the installation process. When comparing the overall installation process (bricks and mortar) of PCM-insulated bricks and standard insulated bricks, the installation time of the former was 10% faster than the latter. When comparing the installation time of the aerogel-insulated render against a standard insulated render, the installation time of the former was 12% shorter than the latter. For the other products, a comparative test was not performed, and a corresponding time analysis was not carried out. The composition of the new wood-fiber panels did not change any characteristic of the product to alter its installation procedure and, therefore, its installation time is considered unaltered.

The results obtained from the performed tests are not representative of typical installation times, given the operations were carried out in controlled environments (laboratories and test cells) and the tests were not repeated in different settings and conditions. Comparative tests were nevertheless performed (USTUTT Lab test and SINTEF Lab test) and the results obtained are significant within the boundary conditions of the test set-ups, by considering the consistency of the parameters (number of operators, skills of operators, physical condition of operators, location of materials with respect to the assembly site, exclusion of idle time) and the above-mentioned limitations.

The target of reducing the installation time of EZ0 products by 30% relative to standard renovation process was therefore not met, due to the following reasons:

- EZ0 focused on the improvement of the physical characteristics of the selected building products by maintaining their installation procedures consistent with their corresponding standard products, thus requiring a set of skills and competences for their installation already known in the building industry of the respective markets.
- A comparative analysis of two products with similar performance but different installation procedures was carried out in SINTEF Lab (section 3.3). The resulting installation time of the insulation (steps 1 to 4) showed that the use of large insulation board (insulation strategy A) saved approximately 35% of the elapsed time. However, when considering the overall process (until step 8), the time saving was just 10%, given the large amount of time needed for the installation of the finishing layer. The characteristic of the mock-up (a simple and flat wall, without recesses and windows) was optimal for the use of the large panels (strategy A), and it was a best-case scenario in terms of complexity of geometry and operations. As mentioned in the interview with the operation, the presence of a more complex geometry

would reduce significantly the time saving of using the large panels because of the need of additional cuts.

- Following the two points above, comparative tests of alternative installation procedures were not carried out in EZ0.