CHEMICAL ENGINEERING TRANSACTIONS

VOL. 94, 2022

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

**ISBN** 978-88-95608-93-8; **ISSN** 2283-9216

DOI: 10.3303/CET2294095

# Comparative Life Cycle Analyses of Regular and Irregular Maintenance of Bridges with Different Support Systems and Construction Technologies

Boglárka Eisinger[a,*], Attila Németh[b], Zoltán Major[b], Orsolya Kegyes-Brassai[c]

[a]Széchenyi István University, Vehicle Industry Research Center, Hungary, 1. Egyetem tér, Győr 9026
[b]Széchenyi István University, Department of Transport Infrastructure and Water Resources Engineering, Hungary, 1. Egyetem tér, Győr 9026
[c]Széchenyi István University, Department of Structural and Geotechnical Engineering, Hungary, 1. Egyetem tér, Győr 9026
eisingerne@ga.sze.hu

The maintenance cost of bridges is huge in every country e. g. in the USA it is (approx.) 41.8 G$. This causes a 6.2 % GHG emission rise annually. Reducing and minimizing cost, GHG level and $CO_2$ pollution is a key factor and a major goal for sustainability. This study presents a comparative life cycle assessment (LCA) of bridges with different support systems and construction technologies but with the same span and location. LCA considers regular and irregular bridge maintenance as well having a great influence on the need and timing for major maintenance or restoration in every 25 to 30 y. Regular maintenance means every 1 - 5 and 10 - y minor maintenance works take place. The analysis is based on primary data collected in Hungary examining fully constructed bridges. For the LCA, the cost of maintenance over a 100 y timespan is based on NIF regulations, the total rate of $CO_2$ pollution and the EF (Ecological Footprint, Gha) level is used (Long et al., 2020;). In practice the maintenance of the bridges take place occasionally when the damage on the bridges are already visible and cannot be postponed based on the in - depth interviews with experts. It is assumed that the cost, EF and $CO_2$ pollution of the regular maintenance over the examined timespan is less compared to results of the irregular life cycle model. Based on the case study presented, it can be concluded that the cost of LCA for regular bridge maintenance is 637,348.32 (k€) and for irregular bridge maintenance it is 994,415.12 (k€). The $CO_2$ pollution for regular bridge maintenance is 12,948.24 (kt) and for irregular bridge maintenance is 13,876.86 (kt). The EF pollution for regular bridge maintenance is 3,237.06 (kGha) and for irregular bridge maintenance it is 3,469.22 (kGha). Considering the long - term sustainability aspects, it is recommended that the maintenance should be a regular and a controlled activity. It is vital to draw the attention of the decision makers, the legislators of the businesses, the maintenance operators, and the inspectors to these sustainability aspects.

## 1. Introduction

Bridge maintenance is a key factor in maintaining continuous transportation. It "is an essential social infrastructure for daily life" (Ishibashi et al., 2020). However, continuous maintenance is needed to achieve continuous and good quality operation. In recent years, several accidents, including fatalities, have occurred worldwide due to neglect of continuous maintenance, for example in 2018 a bridge collapsed during a heavy rainstorm in Genoa killing 43 people (American Scientist, 2018). Prolonged maintenance, or possibly rebuilding of bridges due to lack of ongoing maintenance has a number of additional negative factors, e.g. increased transport cost, negative social impacts, increased $CO_2$, and GHG emissions (Fózer et al., 2020). In 2015, the UN adopted the Sustainable Development Goals (SDGs), which set 17 targets for 2030: “By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource - use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities” (UNDP, Sustainable Development Goals, 2015). Global targets in the document require infrastructure (Martek et al., 2019) planning to be sustainable until 2030. Several studies investigate sustainability analysis of different infrastructures, such as construction (Huang et al., 2020), retaining walls (Balasbaneh and Marsono, 2020), road pavements (Santos et al., 2017) and buildings

Paper Received: 15 April 2022; Revised: 10 June 2022; Accepted: 15 June 2022
Please cite this article as: Eisinger B., Németh A., Major Z., Kegyes-Brassai O., 2022, Comparative Life Cycle Analyses of Regular and Irregular Maintenance of Bridges with Different Support Systems and Construction Technologies, Chemical Engineering Transactions, 94, 571-576 DOI:10.3303/CET2294095

(Sánchez - Garrido and Yepes, 2020). In recent years, however, there has been an increasing focus on sustainability studies of bridges. Not only because bridges are the most important elements of transport infrastructure (García - Segura et al., 2017) but are also recognized as the largest emitters of $CO_2$ (Wang et al., 2021). Studies have been carried out on sustainability of bridges in several dimensions: reducing economic impact during the construction of bridges (Penadés - Plà et al., 2020), optimizing the cost associated with the maintenance of bridges (Sabatino et al., 2016;) maintenance strategy (Navarro et al., 2018).

## 2. Literature of Life Cycle Cost Analysis

Bridges represent an essential element of public transport infrastructure. According to the American Road & Transportation Builders Association (ARTBA) Bridge Condition Report 2021, 36 % of the 220,000 bridges in the US need to be improved, with 79,500 in need of replacement. As an illustration of the severity of the problem, 45,000 bridges are in poor condition, which at the current rate would take 40 ys and would cost 41.8 G$ to maintain. Motorists cross these poor bridges 171.5 M times/d. In Japan, out of the 400,000 highway bridges, 18 % are over 50 y old and 43 % are 43 y old or older. In China the bridges in use (658,100) are in a deteriorated state, but their maintenance needs exceed their capabilities. In Korea, the number of bridges is expected to increase to 11,000 by 2022, with a parallel surge in the number of bridges over 30 ys old. Overall, bridge maintenance requires clearly defined performance criteria, structural assessment standards and maintenance procedures (Jeong et al., 2018). Bridges can be maintained in regular or irregular ways. Regular bridge maintenance is the most sustainable. In regular maintenance, minor maintenance works are carried out every 1 - 5 and 10 y, and major maintenances every 25 - 30 y. Nevertheless, the statistics presented above suggest that bridge maintenance practices are irregular worldwide. This leads to greater environmental impacts and greater social disadvantages. Consequently, sustainability issues are neglected. In this paper a case study is presented. The real bridge data in the case study is from Hungary. The aim is to perform a comparative analysis of the cost and environmental impacts of regular and irregular bridge maintenance. Two types of maintenance behavior were examined: (i) cost and emissions of regular bridge maintenance, (ii) cost and emissions of irregular maintenance. Before starting maintenance work on bridges, their conditioning has to be determined. In Austria, a 5 - step scale applies: (1) Very good (No maintenance measures required), (2) Good (Corrections recommended) (3) Satisfactory (Maintenance should take place in the mid - term), (4) Faulty (Maintenance interventions can be substituted by another assessment/special assessment), (5) Bad Repair/renewal works should be initiated immediately (Stipanovic et al., 2017). The difficulty is to assess the real condition of the bridges. Hüthwohl et al. (2011) have shown that manual bridge inspection can be subjective and incomplete, and that there is a growing need to automate existing systems. LCC analysis means comparing different investment alternatives, calculating the total cost, preferably over the whole lifespan (Tóth and Suta, 2021). The guideline for defining LCA methodology ISO 14040:2006 (Environmental management, Life cycle assessment, Principles, and framework). LCC is defined as the attempt to consider all costs over a lifetime, but there are significant differences in the literature on the calculation methods. The following factors are considered in relation to infrastructure LCC: agency cost, user cost, society, and environmental cost (Chandler, 2004). The U.S. Department of Transportation takes a holistic approach, “All of the relevant cost that occur throughout the life of an alternative, not simply the original expenditures, are included. Also, the effects of the agency’s construction and maintenance activities on users, as well as the direct cost to the agency, are accounted for.” (U.S. Department of Transportation, 2002). LCCA consists of five steps: (i) Establish design alternatives (ii) Determine activity timing (iii). Estimate cost (iv). Compute life - cycle cost. The objective is to calculate the total LCCs for each alternative so that they may be directly compared. However, since the present value of dollars spent at different times is different, expected future cost were converted to present value. (v). Analyze the results. The comparison is made by considering agent and user cost. Agency cost incurred by the bridge owner throughout the lifetime of the bridge: design and construction cost, maintenance cost, end of life cos, user cost includes the financial impact of maintenance activities or cost resulting from increased road accidents. Society cost: third party cost, cost incurred by surrounding businesses and environmental cost (Murphy, 2013). The literature review realized the gap of regular and irregular maintenance cost and environmental impact.

## 3. Material and Methods

The present study is processing data from a two-pillar bridge built in Hungary, above motorway M85, raw material is concrete and carbon steel, it was built in 2020 (Figure 1). During the primary research (Table 1), the

Table 1. Production and maintenance cost, CO2 pollution and EF of the motorway bridge M85

| Year | | 0 | | | 1 | | | 5 | | | 10 | | | 30 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost (k€) | CO$_2$ (kt) | EF (kGha) | Cost (k€) | CO$_2$ (kt) | EF (kGha) | Cost (k€) | CO$_2$ (kt) | EF (kGha) | Cost (k€) | CO$_2$ (kt) | EF (kGha) | Cost (k€) | CO$_2$ (kt) | EF (kGha) |
| Construction cost | | 3,043.77 | 2,962.74 | 740.69 | | | | | | | | | | | | |
| Flooring | Flooring signs | | | | 0.73 | 0.26 | 0.07 | 4.58 | 1.29 | 0.32 | 12.25 | 2.58 | 0.65 | 104.00 | 7.58 | 1.89 |
| | Repair | | | | 0.38 | 0.14 | 0.04 | 2.75 | 0.82 | 0.21 | 7.35 | 1.64 | 0.41 | 70.73 | 4.91 | 1.23 |
| Isolation | | | | | | | | | | | | | | 1,064.43 | 644.26 | 161.06 |
| Coating | Salt protection | | | | | | | 19.19 | 15.83 | 3.96 | 44.04 | 31.37 | 7.84 | 409.36 | 93.92 | 23.48 |
| | Coating of bridge bearing | | | | | | | 11.97 | 4.99 | 1.25 | 32.03 | 9.99 | 2.50 | 308.16 | 29.97 | 7.49 |
| Drainage | Cleaning | | | | 0.06 | 0.02 | 0.01 | 0.40 | 0.09 | 0.02 | 1.07 | 0.18 | 0.05 | 10.28 | 0.55 | 0.14 |
| | Repair | | | | | | | 116.16 | 99.83 | 24.96 | 312.89 | 199.74 | 49.93 | | | |
| | Complete replacement | | | | | | | | | | | | | 5,414.30 | 1,006.11 | 251.53 |
| Dilatation | | | | | | | | | | | 8.48 | 1.30 | 0.32 | 81.61 | 3.89 | 0.97 |
| Protection systems | Railings | | | | 0.89 | 1.04 | 0.26 | 4.00 | 4.68 | 1.17 | 8.42 | 9.28 | 2.32 | 294.93 | 77.20 | 19.29 |
| | Pavement | | | | | | | 7.56 | 4.70 | 1.18 | 18.14 | 9.45 | 2.36 | 167.70 | 27.89 | 6.97 |
| | Drain | | | | | | | 5.62 | 4.56 | 1.14 | 11.71 | 8.77 | 2.19 | 142.07 | 27.00 | 6.75 |
| | Stairs | | | | | | | 0.96 | 4.40 | 1.10 | 2.58 | 8.80 | 2.20 | 25.33 | 26.97 | 6.74 |
| Curbs | Monolith | | | | | | | | | | | | | 204.79 | 134.66 | 33.67 |
| Ascending structures | Repair | | | | | | | | | | | | | 53.31 | 17.25 | 4.31 |
| | Steel structure | | | | | | | | | | | | | 66.79 | 9.99 | 2.47 |
| Washing | | | | | 0.45 | 0.13 | 0.03 | 2.15 | 0.61 | 0.15 | 5.76 | 1.23 | 0.31 | 37.46 | 1.57 | 0.39 |
| Other | | | | | 0.42 | 0.11 | 0.03 | 8.11 | 7.76 | 1.94 | 19.70 | 14.28 | 3.57 | 162.47 | 36.61 | 9,.15 |
| Reimbursement of expenses | | | | | 1.43 | 0.00 | 0.00 | 14.79 | 0.01 | 0.00 | 39.59 | 0.01 | 0.00 | 849.31 | 0.36 | 0.09 |
| SUM | | 3,043.77 | 2,962.74 | 740.69 | 4.36 | 1.69 | 0.42 | 198.24 | 149.56 | 37.39 | 524.00 | 298.60 | 74.65 | 9,467.00 | 2,150.60 | 537.65 |

steps necessary for the construction and maintenance of the bridge were agreed upon by a working group with the experts of the company that commissioned the construction of the bridge The data coordination based on the database of the TERC Commercial and Service Provider Ltd. and the National Infrastructure Development Ltd. Following the data collection, the expert group, included academics (Borsos and Szép, 2021) defining the steps for regular and irregular bridge rehabilitation over 100 y. In every 1st, 5th, 10th and 30th y, the bridge maintenance is a must. During the irregular bridge maintenance, we expected a complete maintenance every 20 y. The differences between regular and irregular maintenance ys cycle are detailed in the second table (Table 2). In addition to the cost analysis, we also cover CO2 emissions and the extent of the EF (Gha) load. Our calculations are based on: (1) Bridge production cost, (2) The cost of maintenance, (3) CO2 emissions during production and maintenance, (4) EF (Gha) emissions during production and maintenance (Yang et al., 2020). In the case of the cost analysis, including the inflation rate (6 %), we present the future value. In the case of irregular bridge maintenances, based on expert experience, it can be said that preventive maintenance is lacking, only significant, large - scale maintenances are carried out. Major maintenance concerns the whole bridge, so the overall maintenance in this case should be carried out every 20 y instead of every 30 y.

*Figure 1: Case study for construction and maintenance of the motorway bridge in Hungary*

The second table (Table 2) shows the cost, $CO_2$ and EF pollution of regular (a) and irregular (b) bridge construction and maintenance calculated over a 100 y life cycle. The cost of LCA is for regular bridge maintenance 637,348.32 (k€) and for irregular bridge maintenance is 994,415.12 (k€). The $CO_2$ pollution for regular bridge maintenance is 12,948.24 (kt) and for irregular bridge maintenance it is 13,876.86 (kt).

*Table 2: Maintenance cost, $CO_2$ and EF pollution (a) calculation of regular maintenance (b) calculation of irregular maintenance*

| y | Cost (k€) | $CO_2$ (kt) | EF (kGha) |
|---|---|---|---|
| 1 - 30 | 12,385.94 | 3,237.06 | 809.27 |
| 31 - 60 | 71,138.54 | 3,237.06 | 809.27 |
| 61 - 90 | 408,583.57 | 3,237.06 | 809.27 |
| 91 - 100 | 145,240.27 | 3,237.06 | 809.27 |
| SUM | 637,348.32 | 12,948.24 | 3,237.06 |

*(a)*

| y | Cost (k€) | $CO_2$ (kt) | EF (kGha) |
|---|---|---|---|
| 1 - 20 | 6,488.04 | 2,775.37 | 693.84 |
| 21 - 40 | 20,808.03 | 2,775.37 | 693.84 |
| 41 - 60 | 66,734.17 | 2,775.37 | 693.84 |
| 61 - 80 | 214,025.54 | 2,775.37 | 693.84 |
| 81 - 100 | 686,359.34 | 2,775.37 | 693.84 |
| SUM | 994,415.12 | 13,876.86 | 3,469.22 |

*(b)*

The EF pollution for regular bridge maintenance is 3,237.06 (kGha) and for irregular bridge maintenance it is 3,469.22 (kGha). It is established that all three indicators have lower values for regulated bridge maintenances than for irregular ones. It is conceivable that for professionals, a regulated bridge maintenance may seem more costly than an irregular one at first. If the life cycle of a bridge (100 y) is considered, it can be concluded that the regular bridge maintenance is significantly more cost - effective and has a lower environmental impact, than the irregular one.

## 4. Conclusions

Maintenance of bridges is a major challenge worldwide in terms of both cost pollution and sustainable development. Bridges are most often maintained in an irregular way, with significant cost and pollution. Designing and renovating bridges, the primary goal is to reduce costs. This is also true for material selection, construction, and maintenance. Environmental and sustainability considerations are often not important and have no decision-making value. The study describes the data for a specific bridge which was built in Hungary, along the motorway M85, in 2020. Based on the case study presented, it can be concluded that the cost of LCA for regular bridge maintenance is 637,348.32 (k€) and for irregular bridge maintenance it is 994,415.12 (k€). The $CO_2$ pollution for regular bridge maintenance is 12,948.24 (kt) and for irregular bridge maintenance it is 13,876.86 (kt). The EF pollution for regular bridge maintenance is 3,237.06 (kGha) and for irregular bridge maintenance it is 3,469.22 (kGha). This study draws attention to the fact that irregular bridge renovation has significantly higher cost and environmental impact in the long run. After the bridges are constructed, the experts should plan the process of regular bridge renovation. This approach contributes greatly to sustainable development.

### 5. Acknowledgments

The research presented in this paper was funded by the “Thematic Excellence Program – National Challenges Subprogram – Establishment of the Center of Excellence for Autonomous Transport Systems at Széchenyi István University (TKP2020 – NKA - 14)” project.

### 6. References

American Scientist, What Happened to the Genoa Bridge?, 2018, <www.americanscientist.org/article/what-happened-to-the-genoa-bridge> accessed 20.02.2022

ARTBA, Bridge Conditions Report, 2021, <www.artbabridgereport.org/reports/2021-ARTBA-Bridge-Report.pdf> accessed 15.02.2022

Azizinamini A., Power E.H., Myers G.F., Ozyildirim H.C., Kline E.S., Whitmore D.W., Mertz D.R., 2014, Design guide for bridges for service life (No. SHRP 2 Report S2-R19A-RW-2). DOI: 10.17226/22617

Balasbaneh A.T., Marsono A.K.B., 2020, Applying multi-criteria decision-making on alternatives for earth-retaining walls: LCA, LCC, and S-LCA. The International Journal of Life Cycle Assessment, 25(11), 2140-2153. DOI: 10.1007/s11367-020-01825-6

Borsos A., Szép J., 2021, Innovation in bridge construction: Results of a construction GINOP project, MÉRNÖK ÚJSÁG XXVIII. 1, 35-38.

Chandler R.F., 2004, Life-cycle Cost Model for Evaluating the Sustainability of Bridge Decks: A Com- parison of Conventional Concrete Joints and Engineered Cementitious Composite Link Slabs: a Thesis Submitted in Partial Fulfillment. Master of Science (Natural Resources and Environment). University of Michigan. <www.researchgate.net/publication/252903807_Life-Cycle_Cost_Model_for_Evaluating_the_Sustainability_of_Bridge_Decks> accessed 08.02.2022

Environmental management, Life cycle assessment, Principles and framework (ISO 14040:2006), <www.standards.iteh.ai/catalog/standards/cen/2931c03a-5600-4028-a3d6-2c40c55e2a6f/en-iso-14040-2006> accessed 14.02.2022

Fózer D., Volantb M., Passarini F., Varbanov P.S., Klemeš J.J., Mizsey P., 2020, Bioenergy with carbon emissions capture and utilisation towards GHG neutrality: Power-to-Gas storage via hydrothermal gasification, Applied Energy, DOI: 10.1016/j.apenergy.2020.115923

García-Segura T., Yepes V., Frangopol D. M., Yang D. Y., 2017, Lifetime reliability-based optimization of post-tensioned box-girder bridges. Engineering Structures, 145, 381-391. DOI: 10.1016/j.engstruct.2017.05.013

Huang M., Zhang X., Ren R., Liao H., Zavadskas E.K., Antucheviciene J., 2020, Energy-saving building program evaluation with an integrated method under linguistic envi- ronment. Journal of Civil Engineering and Management, 26(5), 447–458. DOI: 10.3846/jcem.2020.12647

Huthwohl P., Lu R., Brilakis I., 2011, Challenges of bridge maintenance inspection. <www.scholar.google.com/scholar?hl=hu&as_sdt=0%2C5&q=Challenges+of+bridge+maintenance+inspection+Philipp+Hüthwohl1%2C+Ruodan+Lu2%2C+Ioannis+Brilakis3&btnG=> accessed 29.01.2022

ISO (International Organization for Standardization), 2006, Environmental Managment—Life Cycle Assessment—Principles and Framework; ISO: Geneva, Switzerland.

Ishibashi K., Furuta H., Nakatsu K., 2020, Bridge Maintenance Scheduling in Consideration of Resilience Against Natural Disasters. Frontiers in Built Environment, 6, 179. DOI: 10.3389/fbuil.2020.574467

Jeong Y., Kim W., Lee I., Lee J., 2018, Bridge inspection practices and bridge management programs in China, Japan, Korea, and US. Journal of Structural Integrity and Maintenance, 3(2), 126-135. DOI: 10.1080/24705314.2018.1461548

Long X., Yu H., Sun M., Wang X.C., Klemeš J.J., Xie W., Wang C., Li W., Wang Y., 2020, Sustainability evaluation based on the Three-dimensional Ecological Footprint and Human Development Index: A case study on the four island regions in China. Journal of Environmental Management, 265, 110509.

Martek I., Hosseini M.R., Shrestha A., Edwards D.J., Durdyev S., 2019, Barriers inhibiting the transition to sustainability within the Australian construction industry: An investigation of technical and social interactions. Journal of cleaner production, 211, 281-292. DOI: 10.1016/j.jclepro.2018.11.166

Murphy N., 2013, Feasibility Analysis of a Fiber Reinforced Polymer Bridge <www.diva-portal.org/smash/get/diva2:639694/FULLTEXT02> accessed 18.02.2022

Navarro I.J., Yepes V., Martí J.V., González-Vidosa F., 2018b, Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks. Journal of Cleaner Production, 196, 698–713. DOI: 10.1016/j.jclepro.2018.06.110

Penadés-Plà V., García-Segura T., Yepes V., 2020, Robust design optimization for low-cost concrete box-girder bridge. Mathematics, 8(3), 398. DOI: 10.3390/math8030398

Sabatino S., Frangopol D.M., Dong Y., 2016, Life cycle util- ity-informed maintenance planning based on lifetime func- tions: optimum balancing of cost, failure consequences and performance benefit. Structure and Infrastructure Engineering, 12(7), 830–847. DOI: 10.1080/15732479.2015.1064968

Sánchez-Garrido A.J., Yepes V., 2020, Multi-criteria assess- ment of alternative sustainable structures for a self-promot- ed, single-family home. Journal of Cleaner Production, 258, 120556. DOI: 10.1016/j.jclepro.2020.120556

Santos J., Flintsch G., Ferreira A., 2017, Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. Resources, Conservation and Recycling, 116, 15-31. DOI: 10.1016/j.resconrec.2016.08.025

Stipanovic I., Chatzi E., Limongelli M., Gavin K., Allah Bukhsh Z., Skaric Palic S., Xenidis Y., Imam B., Anzlin A., Zanini M., Klanker G., Hoj N., Ademovic N., 2017, WG2 Technical Report, Performance Goals for Roadway Bridges Of Cost Action TU 1406, ISBN: 978-3-900932-41-1 <www.eurostruct.org/repository/tu1406_wg2.pdf> accessed 06.02.2022

Tóth Á., Suta A., 2021, Global Sustainability Reporting in the Automotive Industry via the eXtensible Business Reporting Language. Chemical Engineering Transactions 88, 1087-1092. DOI: 10.3303/CET2188181

U.S. Department of Tranportation, 2002, Life-Cycle Cost Analyses Primer, <www.fhwa.dot.gov/asset/lcca/010621.pdf> accessed 23.01.2022

United Nations Development Programme, Sustainable Development Goals, <www.undp.org/sustainable-development-goals> accessed 05.03.2022.

Wang L., Fan Y.V., Jiang P., Varbanov P.S., Klemeš J.J., 2021, Virtual water and $CO_2$ emission footprints embodied in power trade: EU-27, Energy Policy, 155, 112348, DOI: 10.1016/j.enpol.2021.112348.

Yang L., Wang Y., Wang R.R., Klemeš J.J., Almeida C., Jin M., Zheng X., Qiao Y., 2020, Environmental-Social-Economic Footprints of Consumption and Trade in the Asia-Pacific Region. Nature Communications. <www.nature.com/articles/s41467-020-18338-3> accessed 06.01.2022