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Modeling the urban stock and lifecycles of bridges: An integrated framework for dynamic-locational material flow analysis

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A R T I C L E I N F O

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A B S T R A C T

The paper introduces a dynamic-locational MFA model to analyze the urban stock of bridges by integrating quantity, time, and location in one framework. The model is developed to assess existing materials in the urban stock, predict future demolition activities, quantify material flows, and analyze their spatial distribution. The derived framework depends on the structural conditions to anticipate lifetime and survival. For the empirical analysis and demonstration, a dataset of >12,000 bridges in North Rhine-Westphalia was compiled to provide the required information such as location, area, type and material. The analyses demonstrate significant variability in material flows across different times and locations. Some regions exhibited exceptional material flows, while others had very low flows, highlighting the importance of temporal and spatial aspects. The results also predict significant material flows over the next two decades in the investigated region, underscoring the urgency of circular economy and closer cooperation between stakeholders.

1. Introduction

As our built environment evolves, reconsidering construction methods and material consumption is crucial to promote sustainability and resilience. Herein, circular economy emerges as a promising approach to minimize waste streams, reuse materials, and regenerate resources. The term urban stock refers to the materials and products within the built environment that persist over time in the anthroposphere, which includes all human activities and their environmental impacts (Baker-Brown, 2021). The urban stock includes various structures categorized as mobile or non-mobile, with non-mobile stock including buildings and infrastructure such as bridges (Lanau et al., 2019). In this regard, urban mining plays a pivotal role in the circular economy by recycling and reusing the materials that exist in the urban stock (Bender and Bilotta, 2020). Therefore, understanding urban stock and material flows from construction and demolition activities is essential, as circular business models require accurate mapping of relevant materials. In most cases, current material flow analysis approaches neglect infrastructure components such as bridges, limiting the effectiveness of circular economy strategies. This study addresses this limitation by developing a comprehensive framework that integrates quantity, temporal dynamics, and spatial distribution into a unified model. The proposed methodology facilitates the assessment of bridge infrastructure stock, forecasts material flows over time, and enables spatial analysis of demolition activities.

There are two main approaches to analyze urban stock (top-down and bottom-up). The top-down approaches use the mass balance principles and statistics to understand the stock dynamics. On the other hand, the bottom-up approach systematically counts the material aggregates of each object and adds them up to determine the total stock. This often involves multiplying material quantities by intensity values in a coefficient-based approach (Schiller et al., 2017). In terms of time consideration, the frameworks can be also classified into two main categories (static and dynamic). While the static approaches aims at quantifying the existing stock and material flows, the dynamic ones considers the material flows over time (Baker-Brown, 2021).

The theme of urban stock has witnessed an obvious momentum in the literature. Urban stock analysis as well as modelling of the resulting material flows from the building stock have been carried out for various countries. Herein, various methods are used to analyze the urban stock, such as statistical and empirical approaches, GIS or material flow analysis (MFA). In particular, MFA is widely utilized in several studies and has been extended further to spatial and/or temporal dimension (Abdelshafy and Walther, 2023). Determining the amount and location of material flows helps policy makers to target interventions and develop strategies. The temporal aspect is also significant, as

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information about the timing of material accumulation is essential for circular economy planning.

As demonstrated in (Abdelshafy and Walther, 2023), integrating both location and time into MFA models is important to enhance the analytical capabilities, especially while addressing circular economy in the construction sector. While stock-driven MFA models can offer valuable insights for various applications, sectors like construction may be influenced by location and time. This is due to the relatively low value of construction materials and the continuous changes in the relevant material flows overtime. Therefore, urban stock studies have worked on integrating the spatial and temporal aspects in MFA models (Haberl et al., 2021; Lanau and Liu, 2020; Roy et al., 2015). For example, (Heeren and Hellweg, 2019) modelled the material flows from Swiss residential buildings in both temporal and spatial terms. (Sartori et al., 2016) also analyzed the Norwegian dwelling stock in their material flow analysis, while (B. Müller, 2006) did a similar analysis on the dwelling stock in The Netherlands. These are only selected examples, many other analyses can be found in the literature in which the urban stock and construction and demolition waste (CDW) material flows are determined.

Despite the improvements achieved in these studies, there are still some thematic and methodological knowledge gaps in literature. The infrastructure systems of bridges are overlooked with roughly no study providing comprehensive analyses on the theme. Herein, key issues include the lack of detailed calculations of the materials stored in bridges and the limited understanding of their dynamics and lifecycles. Although we may find some publications that take infrastructure into account, the bridges are still omitted. For example, the study of (Tanikawa et al., 2021) used GIS to determine Japan's in-use urban stock. Herein, roads, railways and pipe networks were taken into account, whereas tunnels and bridges were not integrated in the model. (Schiller et al., 2017) also conducted similar research by focusing on the infrastructure urban stock of Germany. Herein, the transport infrastructure was also considered, but only the urban stock of roads, railways as well as waterway and airway transport infrastructure. Existing governmental datasets, such as (BASt, 2023a; DOT, 2023), offer extensive bridge inventories. However, they lack specific information concerning the materials used during the construction process.

Studying the survival of bridges is also another research gap, especially when considering an extensive inventory of such structures. In this regard, researchers have developed prediction curves to forecast the condition of bridges over time using deterministic and stochastic models (Fick and Bell, 2022). Deterministic models are based on regression analysis and assume an average lifetime or a specific trend of deterioration. On the other hand, stochastic models account for randomness by using state-based models such as Markov chains or time-based models with probability distributions such as the Weibull distribution (Srikanth and Arockiasamy, 2020). AI methods, including machine learning and neural networks, were also used to predict bridge deterioration by learning patterns from historical data (Fick and Bell, 2022). Herein, each approach has pros and cons: deterministic models are simple but unrealistic, stochastic models handle randomness but require extensive data, and AI methods are promising but still evolving.

Given the large quantities of materials stored in the infrastructure systems, they are of high relevance for circular business models. As infrastructure systems form an essential pillar of our modern society with construction activity set to continue, assessing the urban stock development is essential for monitoring resource use and identifying circular strategies to minimize it. Tracking the bridges' stock is not only limited to circular economy applications, but also associated with other crucial economic aspects (Gaus and Link, 2020). For example, there are around 5000 bridges in Germany that require renovation or replacement, necessitating substantial financial resources (Kinkartz, 2024). A bridge's closure can also have far-reaching and often unnoticed consequences, especially in industrialized economies. An illustrative example in Germany is the closure of the Rahmede Bridge in 2021 due severe damages. According to one estimate, the negative impacts of the closure of this bridge due to longer trips and economic losses amount to at least 1.8 billion euros (Ewald et al., 2022).

Hence, this study aims at deriving a comprehensive framework to analyze the urban stock of bridge infrastructure and predict future material flows. Herein, a methodology for determining the survival of bridge structures is derived. A case study is also analyzed to demonstrate the model and conduct the empirical analysis. Herein, the German federal state of North Rhine-Westphalia (NRW) is selected as a region of interest due to its extensive transportation network and diverse bridge stock. Such infrastructure system can offer significant circular economy potentials. In addition, NRW's diverse topography and historical development of the infrastructure system add complexity to the bridge stock, requiring detailed and advanced analysis. In terms of paper structure, the derived framework and relevant methods are presented in the next section. Afterwards, the results and relevant implications are illustrated in the third section. Finally, the last section concludes the paper with the key outcomes and an outlook for future research.

2. Methodology

The framework of the dynamic-locational MFA (DL-MFA) model is depicted in Fig. 1. The first step involves generating the inventory database, which is pivotal for conducting the empirical analysis and demonstrating the model. Herein, different databases are merged to ensure a comprehensive coverage. The final database includes the key information of each bridge such as construction year and ratings. Subsequently, the initial two methods of the model (content and survival assessments) are applied to each entry in the inventory database. This process generates a database containing material quantities, survival, and expected demolition times for each bridge. The bridge content is calculated based on the bridge's type and area. The demolition year is anticipated based on the construction year and the bridge's survival. The intermediate result is a database with all information about quantities and time (QT-database). In order to conduct the spatial evaluation, it is crucial to export the database into a GIS program. This marks the point where the third assessment pillar is integrated into the model (i.e. location). The resulting model enables the mapping of material flows across both temporal and spatial dimensions. The implementation of GIS allows for regional material flow analysis. Concurrently, the underlying QT-database can be utilized for a variety of other assessments and analyses. The following sections provide more information about the model components.

2.1. Inventory dataset

The inventory dataset is compiled based on two datasets obtained from Autobahn GmbH and Straßen.NRW (Autobahn AG, 2023; Straßen.NRW, 2023). The bridges assigned to federal highways are included in the Autobahn GmbH dataset (6225 bridges). The dataset of Straßen.NRW contains the bridges that serve both federal and state roads (7632 bridges). As shown in Table S1 (Supplementary Information – SI), both datasets contain the key information of each bridge such as construction year, type, length, area, Substance Condition Rating (SCR), Load Index (LI) and coordinates. The dataset of Straßen.NRW contains additional relevant data such as General Condition Rating (GCR). The reference year of both datasets is 2022. The associated ratings are based on inspections conducted in 2022 and previous years, depending on each bridge's individual inspection cycle. Both datasets are then harmonized to make sure they have the same structure and there is no duplication. As the input data includes bridges from different authorities, overlaps are unlikely, but a check was made for duplicates using Bridge IDs.

Due to the wide range of bridge types in the datasets, all entries have been classified into the main four categories used in the study (prestressed concrete, reinforced concrete, steel, and steel composite). These four bridge types cover nearly all federal bridges in Germany,

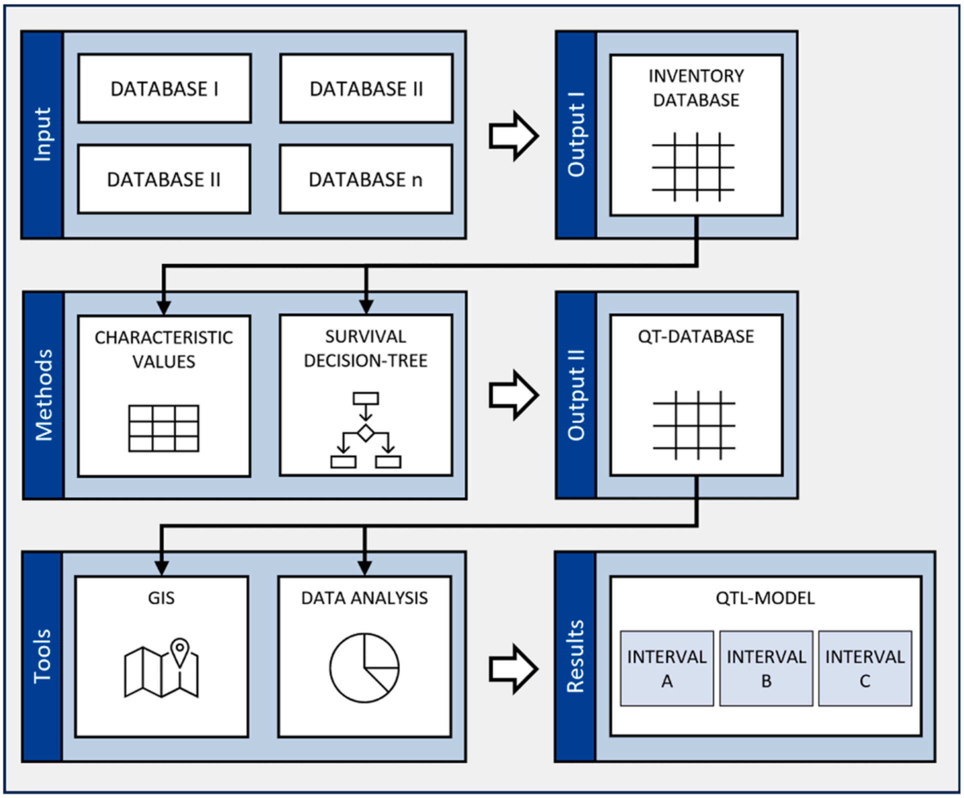

Fig. 1. Framework of the DL-MFA model.

accounting for 99.5 % of their surface area. The remaining 0.5 % are classified as stone, wood or undescribed (BASt, 2023b). The bridge classification has been aligned with ASB-ING (ASB-ING, 2013). Entries of stone and wooden bridges, culverts and Temporary bridges are removed. Besides the content-related aspects, data gaps were also regarded despite being minor. When information such as the year of construction, dimensions, or material class is missing, the entry is omitted. In cases where the SCR is unavailable, GCR is used as a substitute. If both the SCR and GCR are missing, the entry is removed. If the LI data is missing, the bridge will follow the performance approach (to be discussed later). Following the data cleansing, the final dataset comprises 12,410 bridges.

2.2. Content assessment

The objective of the content assessment is to determine the quantity of materials contained within the existing bridges. Given the absence of official records tracking material used during construction, the study adopts a top-down approach by using the material intensities per bridge type and area. The material intensities are derived from a study conducted by the German Federal Environmental Agency and encompass the following materials: construction steel, prestressing steel, reinforcing steel, and concrete for various bridge types (Table S2, SI) (Mottschall and Bergmann, 2013). The material content in each bridge is then calculated by multiplying the intensity values by the deck area ($Quantity_i = Factor_i * Area_{deck}$). In order to validate the intensity values, they should be contrasted with other references. However, it is not easy to carry out such comparison, since structured data on bridge material intensities is very scarce, even among the relevant authorities. Herein, the German Federal Ministry of Digital Affairs and Transport publishes a yearly report presenting bridges and tunnels that were built in the previous year. What is special about these publications is that they contain technical information about the structures and quantities of consumed materials. Additionally, as those reports focus on Germany, their scope aligns well with the context of this study. Accordingly, a separate dataset comprising 26 bridges across different types was assembled (BMDV, 2014, 2016, 2019, 2022). Analyzing the compositions of those bridges and comparing them with Table S2 demonstrates a very high accuracy with R2-values of 0.92 for steel and 0.94 for concrete.

2.3. Temporal assessment

The temporal evaluation entails the assessment of the survival of bridges to calculate their expected lifetime and future material flows. Herein, the assessment approaches can be classified in two categories (i.e. generic and specific). In a generic approach, a constant lifetime is assumed across all bridges, overlooking bridges' attributes, performance parameters and structure-related indices. In this case, generic values from literature or regulations are applied. For instance, (Müller, 2014) adopts a general 100-year lifetime and the ABBV[1] regulation assigns a service life of 70 years to prestressed concrete superstructures (BMJ, 2010). On the other hand, the specific approaches incorporate the bridge's performance and conditions to evaluate its survival, which align better with real-world conditions. However, the difficulty of the specific approaches arises from the highly complex deterioration processes of the bridges. The study has derived a specific approach based on two methods: the performance approach and the protocol approach, which both consider the bridge's conditions and performance by using some metrics such as Substance Condition Rating (SCR) and Load Index (LI).

According to the guidelines for the planning of maintenance measures on engineering structures in Germany, the performance of bridges should be monitored and assessed based on these parameters (SCR and

[1] ABBV: Ablösungsbeträge Berechnungsverordnung (EN: regulation for calculating redemption amounts)

LI) (BMDV, 2020). These parameters are documented through regular structural inspections to evaluate the bridge's conditions. The performance approach is based on the SCR index, which evaluates the stability and durability of the structure. The relationship between SCR and bridge's age can represent the deterioration pattern over time, as shown in Figure S1 (SI) (BMDV, 2020). Using this function from the German guideline for the strategic planning of maintenance measures on engineering structures, the actual SCR of a bridge is compared to its theoretical age derived from the deterioration pattern. Accordingly, it can be determined whether bridges are performing adequately for their age or might have a shortened or lengthened lifetime. The difference between the theoretical age and the theoretical maximum lifetime yields the remaining lifespan of the bridge. The theoretical age is the age assigned to the bridge's SCR of a bridge according to the function, and the theoretical maximum lifetime is assumed to be 120 years, based on (Müller, 2014). Survival is then calculated by adding the remaining lifespan to the bridge's age at the time of inspection.

As SCR mainly considers the endogenous factors, the protocol approach is integrated to address the exogenous aspects, e.g. overloading due to increased traffic. Herein, the protocol approach is based on the Load Index (LI), which compares the actual load on the bridge compared to its design load. Recognizing their significant impact on traffic, a predefined protocol was developed that focuses on the bridges built on federal highways and roads (Kindl et al., 2022). As can be expected, as the LI gets higher, the bridge also gets higher priority. As shown in Figure S2 (SI), bridges are firstly classified into three pre-selection levels based on the LI. Recommendations for action are then derived based on both LI and SCR, integrating structural conditions into the decision-making process. For bridges in preselection levels requiring replacement or modernization, survival is determined based on age and remaining lifespan. Bridges under modernization are assumed to last a maximum of 100 years post-upgrade. For those not requiring immediate action, the performance approach is used to assess survival.

Eventually, both approaches (performance and protocol) are combined into a single framework to build a comprehensive survival model. Herein, a decision tree is developed to categorize the entries and determine the most appropriate approach for each bridge (Fig. 2). Based on the attributes LI and road type, the first step in the decision tree determines whether the performance or protocol approach should be used. If a bridge is designated for a federal highway or federal road with an LI value greater than or equal to 2, we employ the protocol approach. The equations S3-S4 originate from the technical recommendations in the above-mentioned protocol. For all other bridges, the performance approach is utilized as criticality is not applicable to these structures. The bridges that fall into preselection level 0 are assigned to the performance approach, which has one pathway to evaluate the bridges. On the other hand, a further distinction must be made for the protocol approach to assign the appropriate survival assessment to the bridges. The abbreviations S1-S5 are added to the decision tree to highlight the individual possible outcomes.

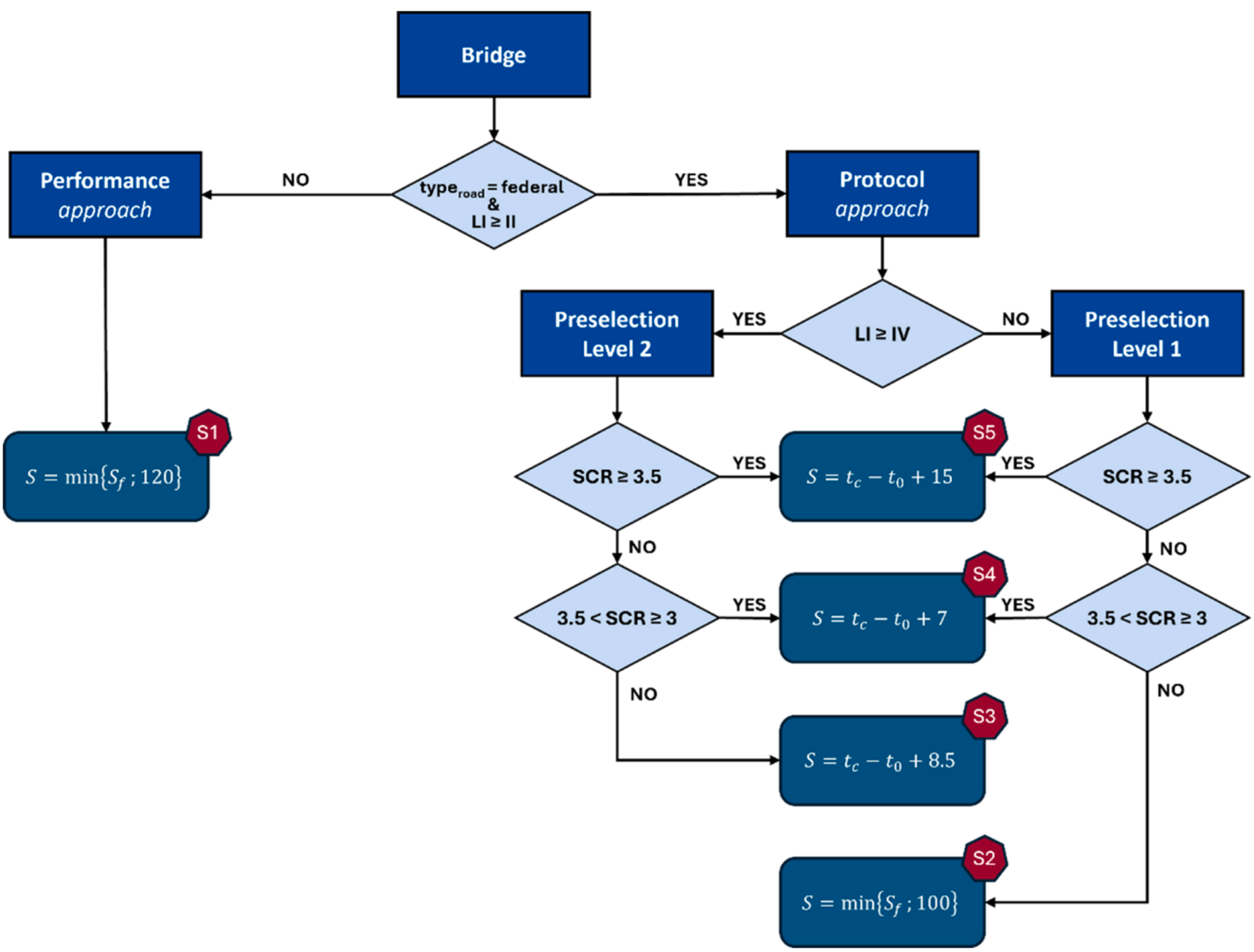

Fig. 2. Derived decision tree for survival assessment.

2.4. Locational assessment

To integrate the spatial dimension into the model and analyses, maps are used to depict the materials flows at different time intervals. This involves the assignment of coordinates to bridges and the utilization of GIS for analysis. After implementing the previous step, the waste streams associated with each bridge and demolition year are estimated. The coordinates of the bridges are then employed to assign each bridge to specific areas on the map. The crucial aspect here is defining the regional boundaries (spatial units). By overlaying the coordinates of the bridges with those of the areas, we detect which bridge corresponds to which spatial unit (Figure S3 – SI). For bridges that span multiple districts, the model assigns them to the district where most of the structure lies. With this bridge-to-spatial-unit assignment in place, the third step entails compiling a dataset for each area, which includes the bridges located within it. This dataset allows us to aggregate the quantities of materials across all the bridges within a particular area. Consequently, we can calculate the total amount of material accumulation in that area over the defined time interval due to bridge demolitions. Choropleth maps are created with varying color intensities to depict material accumulation levels. This process is then repeated for each material type and interval.

3. Results

Analyzing the final inventory dataset shows that around 52 % of the bridges are constructed using prestressed concrete, followed by reinforced concrete bridges comprising approximately 42 %. Steel and steel composite bridges each make up around 3 % of the entire inventory. In total, the urban stock of investigated bridges contains a total concrete volume of 9,555,036 m^3 and a total steel weight of 2,133,340 t. In terms of road type, federal highways account for approximately 65 % of the total bridge deck area. Federal roads represent 20 %, and state roads constitute 15 % of the total bridge deck area. Similarly, the federal highways contain the largest quantities of materials across the dataset, with federal and state roads showing comparable levels. Similarly, federal highways have the largest average surface area per bridge at 814 m^2, compared to 580 m^2 for federal roads and 310 m^2 for state roads. In terms of material content, approximately 70 % of the total bridge deck area is comprised of reinforced concrete bridges, followed by prestressed concrete bridges at 17 %. Steel and steel composite bridges each constitute slightly under 7 %.

For age structure, Figure S4 (SI) classifies the bridge's stock based on the construction decade. As can be seen, there is a substantial surge in construction activity during the years between 1960 and 1990, with the peak occurring in the 70s. Approximately 72 % of the deck area was built during this 30-year period, while only 5 % was constructed earlier. Since 1990, the number of newly constructed bridges has consistently decreased. Over the past decade, only 728 bridges were built, constituting approximately 6 % of the entire deck area. The age structure indicates that, given their varying distribution across different ages, the bridges will not reach the end of their service life uniformly over the different intervals.

In addition to the age structure, the structural condition of the bridges is also highly relevant. Figure S5 (SI) displays the relationship between SCR and total deck area, closely resembling a normal distribution. A shown, about 41 % of the bridges are in a structural condition between 2.0 and 2.4. The proportion of bridges with a rating lower than 3.0 is relatively low compared to the whole stock. Such profiles impact the patterns of lifecycles and material flows as discussed below. Based on the construction year and survival, the demolition year can be estimated, and the material flows are grouped into the respective time interval. Five intervals were modelled resulting in a total observation period of 100 years. We have restricted our analysis to this period because of the significant increase in uncertainty over an extended timeframe. A century was considered to be a reasonable compromise to represent a longer but still comprehensible period. The t05 interval was left open at the upper limit. Nevertheless, the analysis showed that the end-of-life of all bridges fell within this 100-year period. The time intervals are labeled t01 through t05, with each interval covering a period of 20 years, starting from 2023. Fig. 3 displays the demolition rate, indicating the number of bridges reaching their end-of-life within each interval. In the first interval, 2427 bridges reach their end-of-life, whereas only 500 bridges do so in the second interval. The highest demolition rate is observed in the third interval, with 3518 bridges reaching their end-of-life. The number then declines to 3324 bridges in the fourth interval and 2641 bridges in the fifth interval.

The total material flow in each interval can be derived by aggregating the material content of the bridges that will be demolished during that period. Fig. 4 shows the material flows of concrete in m^3 and steel in t over intervals. Interval t01 exhibits the highest concrete material flow, approximately 3.5 million m^3, constituting 37.1 % of the total concrete stock. Afterwards, the flow declines sharply to approximately 150,000 m^3 in t02, gradually increasing to 22.4 % in t03 and 24.6 % in t04. By t05, the flow had decreased to approximately 1.4 million m^3, which equates to 14.2 % of the stock. In terms of steel, the flow also peaks in t01 with approximately 860,000 tons, representing 40.2 % of the total steel in the urban stock. Subsequent intervals exhibit fluctuations, with a notable decline in t02, reaching only 30,000 tons, or 1.6 % of the total steel stock. The flow gradually increases to 19.9 % in t03 and further to 23.5 % in t04, before reaching just under 320,000 tons in t05 (14.8 % of the total steel stock).

As can be expected, using the derived specific approach instead of the generic method will result in dissimilar outcomes. Assuming a fixed lifetime of 100 years, more than half of the bridges should reach their end of life in t03 compared to only 3.2 % in t01 as more than two-thirds of the bridges were built between 1960 and 1990. However, our dynamic model shows demolition at 19.6 % in t01 and 28.3 % in t03, suggesting that many bridges reach end-of-life earlier than predicted by the conventional approach. To better understand these shifts, a Sankey diagram is used to illustrate the flow of bridges between demolition intervals using both approaches (Fig. 5). The left side of the Sankey diagram represents the results of the static 100-year lifetime for all bridges, while the right side represents the calculations of our dynamic model. The arrows between the two sides show how bridges move from one interval to another as the survival determination approach is changed. As can be seen, a large number of bridges move from t03 to t01, indicating that these bridges actually need to be demolished earlier, according to our model. This change indicates that the static approach tends to simplify the lifespan of many bridges, whereas our dynamic model offers a more precise prediction.

These outcomes are bound to change if the key model's parameters are adjusted. A reduction in the theoretical maximum lifetime would lead to a downward adjustment of survival expectations, accelerating the transition of bridges into the end-of-life phase and shifting material flows to earlier periods. This effect would be particularly pronounced in the performance-based survival model, where bridges are assigned a

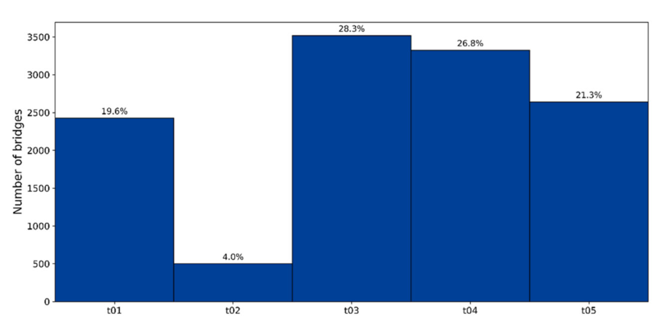

Fig. 3. Demolition rate by total numbers of bridges.

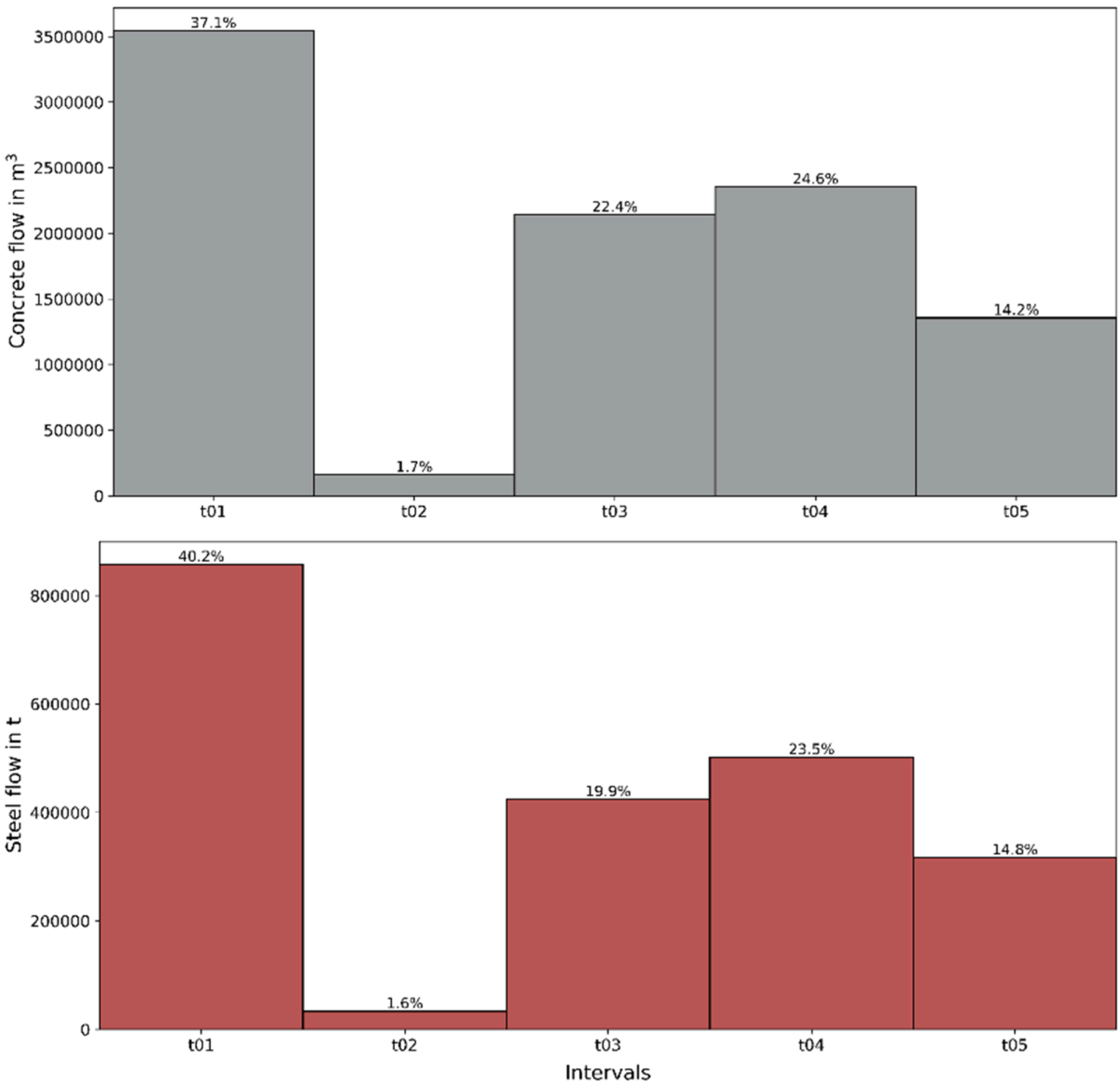

Fig. 4. Material flows of concrete (top) and steel (bottom).

lifespan limit (e.g., S1: min{S_f, 120}, S2: min{S_f, 100}). If this theoretical maximum lifetime cap were reduced, bridges that previously exhibited longer survival times would be decommissioned sooner, leading to an earlier peak in demolition-related material recovery. Conversely, lowering the SCR thresholds by 0.5 or 1 would impact the preselection criteria for survival extensions, effectively increasing the number of bridges eligible for prolonged service life. For example, reducing the SCR requirement for S5 (SCR $\geq$ 3.5) would result in more bridges receiving an additional 15 years of survival. This shift would lead to postponing material outflows and altering the temporal distribution of resource availability. Overall, the interplay between these parameters significantly affects the temporal distribution of material flows. A lower theoretical maximum lifespan accelerates material recovery, concentrating demolition activities in earlier years, while a reduction in SCR thresholds delays material availability by extending service life.

To determine where the materials will accumulate in the future, choropleth maps were generated for each interval. Five choropleth maps per material type illustrate the regional distribution of material flows within intervals t01 to t05. Districts are colored based on the amount of material flow, with darker colors representing larger flows. The eight-class distribution was chosen to provide a clear visualization of spatial distribution, balancing detail and readability. This number, which can be adjusted for further refinement, was chosen because it provides sufficient granularity without being too complex. Districts were chosen as they are commonly used for road infrastructure analysis and enable regional planning through local administrations. The choropleth maps of concrete and steel flows in the respective intervals are shown in Fig. 6. The calculated material flows for the intervals by district are also included in Table S3 (SI). Two hotspots stand out for both materials across the five intervals: the district of Duisburg in t01 and the district of Hochsauerlandkreis in t04. These two districts show by far the largest

Fig. 5. Shift in the end-of-life of the bridges between the methods.

material flow within an interval. In addition, districts such as Köln, Oberbergischer Kreis, Märkischer Kreis, Unna and Dortmund also show high material flows for both concrete and steel in t01.

The geographical distribution of material flows appears to be strongly influenced by time, with significant variations between intervals. In t01, the material flows are mainly concentrated in the central part of NRW, which includes the Ruhr area and the Bergisches Land to the west of Köln. After the relatively subdued material flows in t02 with no distinct hotspots, new areas with increased material flows emerge in t03 and t04. Particularly in the south-east of NRW increased material flows from bridge demolition becomes apparent. However, the central areas also exhibit a similar behavior during this period. Including the district area into the analysis can also provide an indication of the material flow density. Herein, Duisburg serves as a good illustrative example as it exhibits the highest flow density of concrete and steel of all the districts and intervals. This pattern also applies to the other small districts, especially in the Ruhr area. In t04, for example, districts such as Düsseldorf and Mettmann also have high material flow density, which can be also attributed to their small areas.

4. Conclusions

The findings showcased in this study mark a notable advancement in comprehending the complex urban stock and life cycles of bridges. Tailored specifically for bridge infrastructure, the proposed methodology facilitates a thorough examination of material flows, temporal dynamics, and spatial considerations within the urban inventory. Until now, the dominant assumption has been a generic service life, implying a uniform survival rate for all bridges. The derived approach within this work takes into account factors such as the conditions of individual bridges from regular inspection, as well as traffic loads and structural deficiencies. As a result, survival is calculated individually for each bridge structure using a decision tree. As demonstrated in the results, the difference between both approaches is not trivial and can result in variant outcomes. Upon the availability of data, employing the proposed framework is recommended, as it can yield more precise results and effective strategies.

Applying the derived approach to analyze the bridges in NRW has demonstrated its effectiveness and revealed various insights into the dynamics and complexity of the urban infrastructure. With over twelve thousand bridges examined, along with substantial volumes of concrete and steel, the study reveals significant variations in material flows across different temporal and spatial dimensions. Projections for the next two decades indicate a significant need for replacement, particularly affecting 20 % of bridges, which represent 40 % of the total bridge area and contain substantial amounts of steel and concrete. These findings underscore the impending challenges in managing material flows, with significant fluctuations expected over the next century. Choropleth maps generated from the data pinpoint specific hotspots, highlighting regional

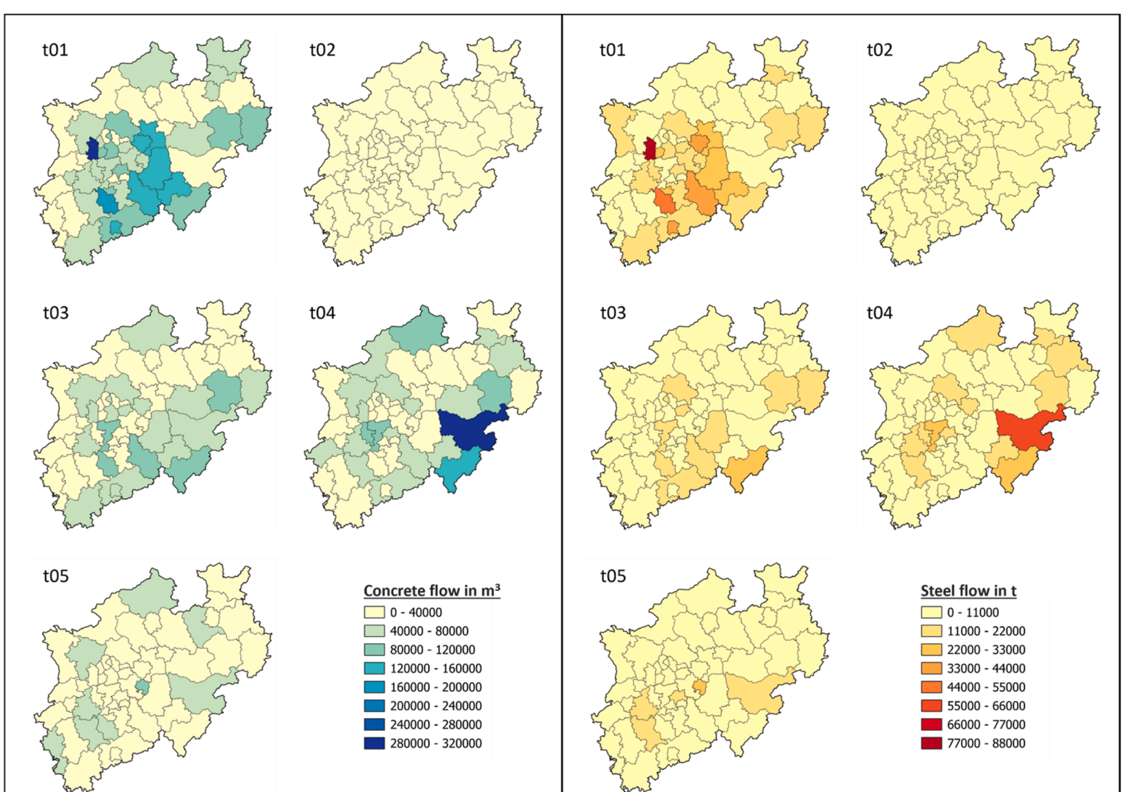

Fig. 6. Choropleth maps of the concrete (left) and steel (right) flows for the five intervals.

disparities in material flows that evolve over time. Understanding these dynamics is crucial for effective long-term planning and resource management in bridge infrastructure maintenance and replacement efforts.

Herein, an important aspect to take into account is the viability of demolishing and replacing the numerous bridges expected to reach the end of their lifespan within the first interval. The accelerated lifecycle of these bridges highlights the urgency to develop and implement circular strategies. Also, given the substantial resources needed to demolish and rebuild complex federal highway bridges, the feasibility of managing such a large volume of projects within 20 years can be controversial. As a result, some bridges in t01 may remain in service longer than predicted due to the limited construction and demolition capacities. Herein, special measures could be implemented to extend the lifespan of some bridges until replacement capacity is available. Such a solution would allow a portion of the demolition and construction activities to be deferred from the first period to subsequent intervals.

Despite these advantages, the study has certain limitations that can be improved further in future research. The dataset excludes some bridges in NRW due to fragmented responsibilities across counties and municipalities, resulting in incomplete coverage. Additionally, the use of characteristic values based solely on deck area may lead to inaccuracies in material estimates for atypical bridge designs, particularly those with complex or non-standard structures. Therefore, including other parameters such as bridge's height can enhance the results' accuracy. The model incorporates design standards and temporal variations through the protocol-approach, with the load index accounting for the limited lifespan of specific bridge types (e.g., prestressed concrete bridges constructed up to 1966 with spans $\geq$20 m), implicitly reflecting shifts in design standard. However, the generic SCR deterioration curve used in the model may not fully capture the nuances of different bridge types, and maintenance activities that could extend the life of bridges are not accounted for, potentially biasing survival estimates. Also, as SCR values can change overtime, analyzing the historical data might result in more reliable results. However, historical rating data is currently unavailable as archiving only began a few years ago. Therefore, applying the derived approach iteratively as more data becomes available in the future can improve the model's accuracy. From a material density perspective, significant differences between historic and modern bridges are unlikely given long-established design and durability standards. However, this assumption has not been verified systematically, and further research is needed to assess the effect of material composition and ageing on structural performance over time. Despite these limitations, they do not diminish the value of the findings. With further data collection and refinement, the model can be applied to other regions and contexts.

Overall, the analyses can support the practitioners and governmental entities to derive suitable strategies and policies for infrastructure and material flow management. Therefore, the analyses are highly relevant to circular business models, particularly in the context of predicting material flows and identifying material hotspots. By forecasting demolition rates and material availability, the study provides key insights for recycling and reuse in infrastructure projects, which are foundational to circular economy strategies. This can support more efficient resource management and planning in future construction and demolition activities. The integration of spatial and temporal aspects with quantities presents a crucial opportunity to enhance construction and recycling systems, facilitating more efficient planning of demolition, recycling, and construction activities. The flexibility of the decision-tree model allows for adaptation to diverse management strategies and protocols, ensuring relevance to specific scenarios and bridge characteristics. Furthermore, the potential for regional variations in material flows underscores the importance of optimizing the locations and capacities of recycling facilities. As demonstrated by this study, there is immense potential for further improvement and application of these methods beyond the current region, promising broader benefits for circular economy and resource efficiency.

CRediT authorship contribution statement

Stefan Lange: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Ali Abdelshafy:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Grit Walther:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108232.

Data availability

Data will be made available on request.

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