RAIL4CITIES

EU-wide SCP Methodology

Deliverable 4.1

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Contributor(s)	Alice Lunardon, Benedikt Boucsein

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Abbreviations and acronyms

Abbreviations / acronyms	Description
FoA	Field(s) of Action
KPI	Key Performance Indicator
LL	Living Lab
PV	Photovoltaic
TOD	Transit-Oriented Development
STOD	Sustainable Transit-Oriented Development
UGI	Urban Green Infrastructure

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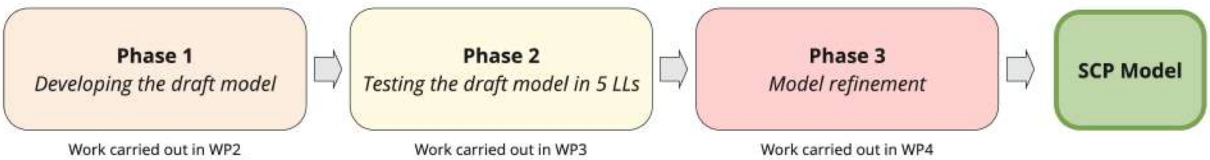
1 Executive summary

The RAIL4CITIES project introduces a new model for current and future railway stations and demonstrates the changes necessary for them to play a significant role in a sustainable urban future. To date, there is a lack of a consistent concept to describe the sustainable transformative potential of railway stations, making it challenging for all stakeholders involved to envision collaborative sustainable transition pathways. Consequently, the objective of the model in the RAIL4CITIES project is to identify common sustainable transformation pathways for European railway stations and thus to emphasize their distinctive role in urban landscapes, not merely as mobility nodes but as integral elements of urban life, impacting a diverse range of stakeholders.

This deliverable describes the development process (c.f. graphical abstract below) and structure of an EU-wide model that prioritizes sustainability based on specific station contexts, users, and local communities. Model development began with a literature review highlighting station diversity, followed by expert workshops that led to a draft model outlining fields of action, performance indicators, and stakeholder engagement methods. The model was then tested in five Living Labs through workshops and user participation, and then further refined in expert sessions. The final model builds on the draft model, enriching it with data collected in the Living Labs. It enhances existing approaches by incorporating qualitative aspects and additional sustainability dimensions, such as social inclusion and circular economy principles, thus highlighting the potential of railway stations as drivers of sustainable urban development. We conclude by discussing challenges throughout the model development process as well as future research questions.

This content has already been published as a pre-print on SSRN under the DOI 10.2139/ssrn.5270242[1]. To avoid content duplications, the pre-print paper serves as the primary element of this deliverable, following the executive summary.

Concerning the RAIL4CITIES project structure, this deliverable summarizes the results of WP4 (T4.1 and T4.2) related to the SCP model and KPIs, as well as the EU-wide methodology following consolidation through the operation of living labs and expert discussions.



[1] *Koulouris, Spyridon Nektarios and Ruf, Stefanie and Lunardon, Alice and Boucsein, Benedikt, A Model for Railway Stations at the Forefront of STOD Urban Transformation. Available at SSRN: https://ssrn.com/abstract=5270242 or http://dx.doi.org/10.2139/ssrn.5270242*

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A model for railway stations at the forefront of STOD urban transformation

Keywords: railway; station; urbanism; TOD; sustainability; transformation; mobility

Glossary:
FoA: Field of Action
KPI: Key Performance Indicator
LL: Living Lab
PV: Photovoltaic
TOD: Transit-Oriented Development
STOD: Sustainable Transit-Oriented Development
UGI: Urban Green Infrastructure

Abstract

Transit-oriented development (TOD) promotes sustainability by pooling urban density near transit services, thereby reducing reliance on private motorized vehicles, lowering greenhouse gas emissions, and fostering walkable, vibrant communities. However, the potential of TOD for sustainable urban transformation beyond mobility and land-use has not been fully explored, particularly regarding ecological and environmental dimensions. Here, railway stations, as key accessibility nodes, have significant potential to support a more holistic approach to sustainability through TOD. However, existing station frameworks and models often overlook aspects of social sustainability and the diversity of stations' possible sustainable transformation pathways. Furthermore, they frequently fail to address the interplay between stations and their surrounding areas as TODs. To address this, the *[XY]* project aimed at developing an EU-wide model that prioritizes sustainability based on specific station contexts, users, and local communities; a process that is described in this paper. Model development began with a literature review highlighting station diversity, followed by expert workshops that led to a draft model outlining fields of action, performance indicators, and stakeholder engagement methods along the line of S-TOD. The model was then tested in five Living Labs through workshops and user participation, and then further refined in expert sessions. The final model builds on previous quantitative TOD approaches by incorporating qualitative aspects and additional sustainability dimensions, such as social inclusion and circular economy principles, thus highlighting the potential of railway stations as drivers of sustainable TOD. We conclude by discussing challenges throughout the model development process as well as future research questions.

Introduction

With cities facing increasing social and mobility challenges like population growth, congestion and pollution (Dodman et al., 2022), Transit-Oriented Development (TOD, Calthorpe 1995) is once again on everyone's lips. Dating back to "much older ideas of rail-based urban development [...] in many European cities during the 19th and 20th centuries" (Pojani & Stead, 2018, p. 94), and concomitant with the introduction of high-speed rail in many European countries, TOD is seen as a tool for the sustainable transformation of the European city, with its patterns of sprawl and car-dependent urbanization (Bertolini et al., 2012).

Within the framework of TOD, authors pledge for an organization of space following a network of nodes, where urban density, activity and transport accessibility are high, thus reducing reliance on car-based mobility and creating vibrant communities (Salat & Ollivier, 2017). Yet, it is being argued "that the development mode advocated by TOD seems to lack relative considerations of both the ecological and environmental dimensions" (Huang & Wey 2019, p. 1-2) and that the mere implementation of TOD spatial planning principles is "inadequate to facilitate a sustainable, livable, natural, and healthy" (Huang & Wey 2019, p. 2) urban communities. Still, TOD as a concept provides a perfect basis for further optimization of urban structure towards sustainability principles (Cervero & Sullivan 2011), especially regarding railway stations (Niu et al. 2021): Among others, the accessibility of stations, pedestrian-friendly station locations, and an urban design framework for station area development (Loukaitou-Sideris & Banerjee, 2000) are TOD criteria that explicitly address the station realm. Considering the pivotal role of stations and their surrounding areas as cores of TOD (Banerjee, 2025, UIC Passenger Department, 2019) which often fall "in the gap between transport and urban agendas, as well as diverging responsibilities, being overlooked by urban planners and policymakers" (*[YY]*, *[year]*, *[page]*), they can act as a perfect laboratory and lever to develop and implement sustainable TOD concepts.

Station area development pathways are often conceptualized through models that serve as a common system of understanding (Zemp et al., 2011), with the most widely recognized model being the Node-Place model (Bertolini, 1999). However, the review of existing models (c.f. chapter "literature review") has shown that these models focus solely on the known aspects of TOD, lacking additional sustainability dimensions, which leads to a deficit in the evolution of railway station areas towards a more sustainable TOD paradigm. This fact has been highlighted by *[YY]* et al. (*year*) and *[XX]* et al. (under review) who have already hinted at the potential for a new inclusive normative framework – e.g. in the form of a model – for the exploration of the potential of transformation pathways for railway stations, with an explicit focus on sustainability.

Therefore, referencing previous station models, the aim of this paper is to describe and reflect on the development process for a new, refined model for railway stations, which was part of the *[XY]* project *(grant details)*. The sustainable transformation pathways highlighted through the model attempt to identify and integrate all important potentials for sustainable TOD in a station and station area, thus supporting "decision making in complex redevelopment processes by helping to develop a common system understanding" (Zemp et al., 2011, p. 447) for designing sustainable TODs.

Literature review

Though literature suggests that until now, "several conceptual models have been developed to support redevelopment processes at railway stations" (Zemp et al., 2011, p. 447), the sustainable transformation of stations and station areas remains a challenging task, where no single model has yet been found that can be applied to all situations, both from a planning perspective and a governance perspective (*[YY]* et al., *[year]*). Additionally, authors highlight there is still a lack of transferable knowledge and that the lack of a "common, cross-stakeholder 'story'" (Thomas et al., 2018, p. 1204) that incorporates station area development as a means to realize multiple goals is still a barrier. Despite this fact, the existing conceptual frameworks can act as a solid reference basis for identifying transformation dynamics and fields where action should be taken for the development of railway station areas. Given our research objective to identify potential sustainable transformation pathways for European railway stations within a model based on the TOD framework, recognizing the necessity of evolving and dynamic approaches to address sustainability challenges (Leach et al., 2010), we focused our literature research on models that transcend the static assessment of stations and rather emphasize key fields where action should be taken, as well as hinting at possible transformative processes on the urban development scale.

A first, very prominent example is the Node-Place (NP) model (Bertolini, 1999), which seeks to investigate the possibilities of TOD in station areas, while emphasizing the two crucial functions of stations: as transportation hubs that facilitate mobility and accessibility within the station area, and as social gathering places that enrich urban life and foster human interaction. The model classifies stations and their surrounding areas into categories, depending on the balance between their role as a transport hub and their function as a vibrant urban place. Newer station development dynamics led to variations of the NP model in literature. For example, Vale et al. (2018) introduced an additional design dimension to the NP model so that it "explicitly incorporates design aspects of the built environment as well as the importance of the walking environment for public transport patronage and overall sustainable urban mobility" (Vale et al., 2018, p. 285), leading to other authors referring to a *Node-Place-Design* model (Zhang et al., 2019). The

NP model and its variations are primarily used for station classification (c.f. *[XX]* et al., under review), yet it proposes possible development pathways for railway station areas through movements within a diagram where the y-axis represents node strength and the x-axis represents place strength, thus illustrating the dynamic potential of station areas to transform depending on the changes in node and place characteristics.

Also addressing the topic of station development using classification, but from the point of view of station and station environment design concepts, Juchelka (2002) classifies station locations in a functional pyramid based on weighted station functions (primary transport/mobility function, secondary retail/leisure functions, and tertiary business/administration functions). In addition, the stations are categorized according to their transport importance, where hierarchy ranges from local or regional stops to top-node stations. By combining the functional levels of importance of a railway station with different restructuring approaches, Juchelka suggests various transformation pathways that are not limited to the station itself but acknowledge its role and interplay with the urban fabric. Such a functional development of railway stations is also the focus of Zemp et al. (2011), who aim to deliver a structured framework focusing on the generic functions of railway stations (e.g. supporting transfer between modes of transport, linking catchment area and transport network, providing public space), as well as their interdependencies (e.g. positive/negative interactions to each other). Thus, they aim to foster a common understanding between different stakeholders who "can use the framework as a basis to find a common language to describe their perspectives and requirements" (Zemp et al., 2011, p. 453).

Differing from the previous approaches, Wulfhorst (2003) presents an exemplary approach for using modeling within the field of system dynamics (using variables that include e.g. land availability, car volume, spatial design) in order to map out the interrelationships between the development of the station and the station surroundings in an overall system. On this basis, he aims to estimate the interactions between the use of space in the station surroundings, the use of the station building, and the transport links at the station, as well as the effects on rail use. The model is intended to make these interrelationships clear and transparent in order to assist strategic development concepts for specific locations and to support appropriate coordination between local stakeholders.

Last but not least and being the only approach focusing primarily on sustainability, Spinosa (2023) proposes a quantitative model for assessing and mitigating the environmental impact of railway stations, treating them not merely as transport hubs but as active agents of urban ecological transition. The core methodology involves calculating a station's ecological footprint, focusing on energy and water consumption, and then proposing mitigation strategies such as renewable energy generation, rainwater harvesting, and urban greening to achieve climate neutrality.

Putting the existing model approaches into perspective, it becomes evident that though they provide robust frameworks in the fields of transport and land use, as well as other key topics such as stations as centers for retail/leisure activities, they still lack a holistic integration of aspects crucial to sustainability in urban systems, such as active mobility (European Commission: Directorate-General for Communication, 2021), circularity (European Commission, 2020), renewable energy production/consumption (UN, n.d.-a), or socially inclusive spaces and practices (UN, n.d.-b). The blue station model (Spinosa, 2023) is an exception to that rule, yet it concentrates exclusively on impact mitigation rather than dynamic transformation and does not address the main functions of railway stations, such as their role as mobility and proximity hubs.

Furthermore, while the importance of the 'people' dimension is recognized in some NP model extensions (e.g. Caset et al., 2019), there is still a need for a stronger focus on the needs and experiences of users and local communities in station area development (*[YY]* et al., *[year]*; *[XX]*, *[YY]*, et al., *[year]*), addressing the topic of social sustainability. A new model for railway stations could move beyond considering users in the form of ridership numbers and explore how stations can act as socially inclusive hubs and cater to the needs of a diverse population. In addition, it becomes evident that the analyzed model approaches lack tangible development and stakeholder cooperation processes for the implementation of their normative guidelines in real-world situations, highlighting the need for integrating stakeholder participation and co-creation formats directly into the structure of future railway station area models (*[YY]* et al., *[year]*), especially since stakeholder cooperation is being highlighted as a crucial topic for TOD (Mouritz and Ainsworth, 2009).

Methods

The development of the aforementioned model for railway stations was divided into three distinct phases (c.f. Figure 1). The (1) first phase involved creating a draft model, which was then (2) tested in five different living labs (LLs). The collected data from the LL processes was (3) used to refine the model once again in the third phase. Since the framework of the *[project]* project did not allow for the collection of mass data for a larger number of European stations (only five representative examples were explored), the refined model version also highlights the steps that need to be taken in the future to validate the model further, contributing to defining more specific sustainability pathways for stations and their surrounding areas. As a foundation for all three phases, a literature review on station classification approaches was conducted in advance (c.f. *[XX]* et al., under review). The review aimed to identify emergent themes used to describe railway stations and surrounding areas, which informed the core components of the model and would later serve as a basis for workshops in phase (3) of the model development. Additionally, it sought to collect classification criteria that could serve as references for key performance indicators (KPIs) that assess the current status of a railway station and its progress towards more sustainable urban futures.

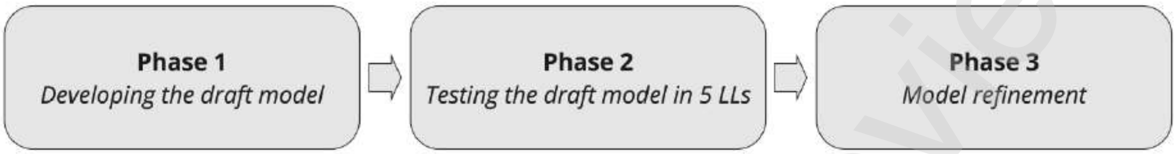

Figure 1: Model development phases

<u>*Phase (1): Development of the draft model*</u>

In the following paragraphs, the steps for phase 1 of the model development are described (c.f. Figure 2 *upper third), namely (step A.) the review of existing station models and consortium workshop to identify key areas for station transformation, (step B.) the first round of workshops with experts to further validate these into fields of action (FoA), (step C.) the second round of workshops to discuss the resulting initial first draft of the model (testing the fields of action and methodological toolkit). These steps resulted in the first, draft version of the model.*

Through the aforementioned literature research, the following three core components were identified as being relevant for a railway station model:

- Fields of action (FoA) as key areas or domains where efforts and initiatives should be focused to transform stations areas into promoters of sustainable TOD. Defining FoA is a common strategy for developing sustainable transformation strategies (e.g. in Presse- und Informationsamt der Bundesregierung, 2012), and it is also highlighted as a step for the development of railway station models (Wulfhorst, 2003).
- A second core component focusing on appraisal, based on assessment criteria (KPIs). These indicators are crucial for measuring the "performance" of railway stations and surrounding areas (Zemp et al., 2011) along pre-defined themes (in this case, the FoA).
- A third core component for a methodological toolkit to facilitate stakeholder cooperation and effectively align their actions with the defined FoA, thereby initiating the station areas' sustainable transformation. The need for effective stakeholder collaboration in the context of TOD and railway station development

is highlighted by many authors, including Mouritz and Ainsworth (2009), and Stadler Benz and Stauffacher (2023).

Steps A and B: Literature review and first round of workshops

Our first priority was to identify the major fields of action (FoA) that are important for the stations' contribution to sustainable urban transformation. These key areas highlight where focused efforts are necessary to drive systemic change toward sustainability within the railway station context. To do this, (step A., c.f. Figure 2, upper part) we looked both at the literature available (see literature review chapter) and initiated a workshop within the *[project]* consortium, where first hypotheses for FoA were formulated (e.g. mobility, station building and architecture, urban development).

Based on Bertolini and Spit's (1998) hypothesis that the development of railway stations is a challenging task because of divergent perceptions by the stakeholders involved, and the same authors' suggestion that it "should be viewed from several perspectives at the same time"(Bertolini & Spit, 1998, p. 4), we developed the draft model through further expert workshops, inviting participants from different relevant sectors, such as railway industry, spatial planning and urban governance. The first expert workshop round (step B.) consisted of three separate sessions, one with 20 experts from railways and industry, one with 14 experts from academia, and one with 8 experts from cities or the field of governance in general. The Cambridge Value Creation methodology (Vladimirova, 2019) was applied to the proposed FoA stemming from the initial consortium workshop, aiming to identify uncaptured value (e.g. yet unidentified potentials) by aligning the interests and needs of different stakeholder groups and exploring their differences. The experts' background included different relevant disciplines, such as urban governance, urban development, urban mobility, station architecture and design, station management and operation, rail systems engineering, transit-oriented development, placemaking, and urban climate adaptation. The experts were from 15 different European countries, in order to capture regional differences in railway station design, usage and development. For every proposed FoA, next to the uncaptured value, the participating experts were asked to identify the value captured (what is currently working well in the current system of station/station area), the value destroyed (what is currently not working well in the current system of station/station area), the value missing (potentials which exist in the station/station area, but are not currently exploited), the value absence (something which is required, but does not exist), and the value surplus (something which exists, but is not necessary).

After the first expert workshop phase, we evaluated the input and grouped it into seven FoA (c.f. chapter "results") for the draft model version. Additionally, reflecting on the discussion in the first expert workshop round (step A.), as part of the draft model, a methodology for exploring each specific FoA within the stakeholder workshops which would take place in the LL process (phase (2) of the model development) was proposed to then be used by local stakeholders in the LLs (including e.g. railway companies and urban governance bodies) in order to elaborate on the applicability of the model FoA in each specific local context. This so-called “methodological toolkit” was based on a modified version of the Cambridge value creation model (Bocken et al., 2013; Vladimirova, 2019).

Step C: Second round of workshops

Before its application in the LLs, the toolkit was tested in three expert workshops (c.f. Figure 2, phase 1, step C. “second workshop round”) which took place after the first expert workshop round described above and which had two main objectives: On the one hand, it aimed to validate the proposed methodology for the model application in the LLs, by using the various experts of the consortium and 24 selected participants from the project’s international advisory board (IAB) with different professional backgrounds as representatives of local stakeholder groups. On the other hand, it aimed at validating each of the model FoA.

Building on the participants’ diverse expertise in the fields of railway and industry, academia or cities and urban governance, we built 10 groups (each consisting of 3-5 people including moderator), each concentrating on one or two of the seven FoA of the draft model in order to develop solutions and strategies together, which would allow the station to make a positive contribution to sustainable urban development. Furthermore, the stakeholders were asked to identify the exact boundaries that would inhibit the direct realization of the proposed strategies, like governance obstacles or spatial factors. As a last step, the workshop participants were asked to identify interventions that would allow for overcoming these boundaries. This step is of particular importance since, in the field of TOD, the early identification of constraints and the involvement of “stakeholders and community members in problem-solving as part of the visioning and planning process can be a fruitful approach” (Mouritz & Ainsworth, 2009, p. 129). The discussion during the workshops took place using a pre-defined digital board structure, where the moderator of each group documented the participants’ contributions. The participants were also given access to the board and could add their own comments as well.

In parallel to the two expert workshop rounds, we used the classification criteria collected in the literature review (*[XX]* et al., under review) as a basis for a consortium workshop to formulate key performance indicators (KPIs) for the sustainable development of railway stations (c.f. Figure 2).

<u>*Phase (2): Validating the draft model in the LLs*</u>

In the following paragraphs, the steps for phase (2) of the model development are described (c.f. Figure 2 middle third). The draft model identified in phase (1) needed to be tested with real-world data, a feat that was aimed for in three steps in phase (2), namely (step A.) involving stakeholders through stakeholder workshops and mapping user profiles through interviews and observation, (step B.) carrying out one ideation workshop for each LL leading to the proposal of solutions, and finally (step C.) validating the solutions through placemaking activities, AI visualizations, and station area design concepts. These steps produced valuable results/data which were used for the refinement of the draft model.

LLs were selected as the primary means to validate the draft model, since they "are emerging as a form of collective urban (…) experimentation to address a range of sustainability challenges experienced in cities" (Voytenko et al., 2016, p. 53). The proposed draft model thus was tested in five different LLs across different European countries (Toulouse Matabiau station, France; Milano Rogoredo Station, Italy; Ottignies Station, Belgium; Tomaszów Mazowiecki Station, Poland; Dorfen Station, Germany). The LL methodology and the development process have been extensively described by *[YY]* and *[XZ]* (submitted for publication), so only a summary is given in this article. The LL stations and station areas had been chosen during the project proposal phase already to represent different station typologies and urban contexts.

Since identifying the opportunities and constraints of a site is essential for TOD implementation (Mouritz & Ainsworth, 2009), as a preparatory step, an analytical profile was developed for each station. Based on this analysis and as a first step in the LL process (phase 2, step A. "involving stakeholders" Figure 2), stakeholder maps were created to identify key players for the LLs and to depict their relationships with the railway provider. Using the methodological toolkit from the draft model, two phases of stakeholder workshops were then carried out, the first one being between the railway provider and local authorities, while the second also included various stakeholders such as shared mobility providers, energy production companies, waste management firms, and real estate investors.

Parallel to the stakeholder workshops, a user engagement phase was conducted, during which user observations and targeted interviews took place, which resulted in the identification of different kinds of user profiles based on the modes of transport used, their perception of the station area, and their movement and actions in space. Furthermore, through the interviews, the station users had the opportunity to introduce further topics that were not already covered by the FoA. Interviews have been extended also to neighbors and citizens living or working in the stations' surroundings.

Based on the user profiles, an ideation workshop (step B. “ideating solutions”) was then carried out for each LL, where local stakeholders collaboratively developed tailored solutions for each user profile (e.g., new spatial arrangements and transport modes, utilization of new technologies, new collaborations, new services) along questions about the requirements and everyday life of each user profile.

The solutions developed were visualized and validated through different approaches (step C. “validating solutions”). First, placemaking actions were implemented to enhance the involvement of users in the station area transformation, allowing participants to collaboratively envision specific aspects of the proposed solutions (Project for Public Spaces, 2007). Second, after discussing their feasibility with the involved railway companies, specific solutions were visualized using AI renderings created using the UrbanistAI software, in order to help all stakeholders better understand the potential of the station’s area.

Lastly, specific proposals were created by translating the proposed solutions into spatial and functional 2D and 3D plans of the station and station area, graphically depicting new spatial and functional relations. For further information about the LL process, the reader is referred to *[YY]* and *[XZ]* (submitted for publication).

<u>*Phase (3): Refining the model*</u>

In the following paragraphs, the steps for phase (3) of the model development are described (c.f. Figure 2 lower third), which aimed at refining the draft model developed in phase (1) based on the real-world data collected in phase (2) by conducting consortium and IAB workshops on FoA and KPIs, resulting in the final model version.

In the third phase of the model development, the FoA, KPIs and structure of the draft model were refined based on the data collected in the LL process, literature review on station classification, and expert input. To do this, first, two workshops were conducted targeting the *[project]* consortium members and IAB experts, respectively, aiming to facilitate a reflection on the model FoA and structure. The workshop participants were provided with the FoA of the draft model, the emergent themes for the description of railway stations (collected through the literature review on classification approaches, *[XX]* et al., under review), and other relevant key topics that were identified through the LL process. The workshop participants were asked to cluster all of these results into new categories, which served as a basis for the definition of the FoA of the final model version. This approach was selected in order to integrate (1) the initial assumptions of the draft model with (2) new data collected in the LLs and (3) with newest insights from literature based on the review on station classification (*[XX]* et al., under review). Furthermore, in each workshop, a discussion took place about the overarching structure of the model.

After the definition of the model FoA, a workshop was conducted with all consortium members to discuss the usability of the KPIs (among others the ones predefined in phase (1)) for the sustainable transformation of the stations. Using the KPIs from the draft model and reflecting on the classification criteria list produced in the literature review about station classification approaches, the workshop participants were asked to select relevant KPIs reflecting on the LL findings and experience, and assign them to the model FoA.

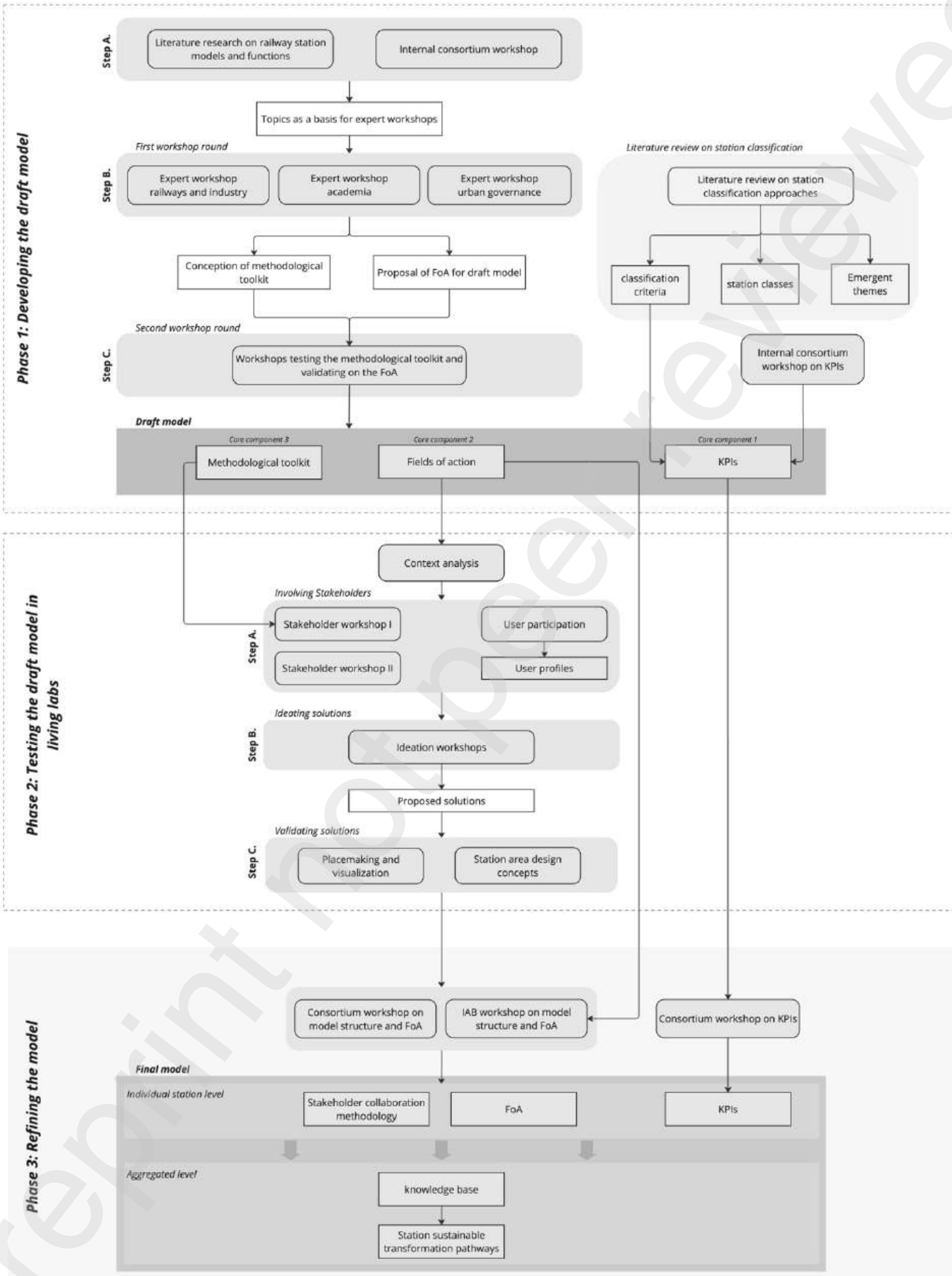

Figure 2: Model development process

Results

Corresponding to the structure of the methods chapter, results are divided into three sub-chapters related to phases (1), (2), and (3) of the model development (c.f. Figure 2), with the final model version being described among the results of phase three.

Phase (1)

The main result of phase (1) is the draft model version, which consists of three core components, namely *appraisal*, *FoA,* and *methodological toolkit* (c.f. Figure 3). As a result of the literature review and first expert workshop phase (Figure 2: phase 1, steps A and B), seven *FoA* were identified. For each FoA, specific KPIs were proposed which allow the *appraisal* of the station situation both in the present as well as in the future, e.g. during transformation processes. The FoA and corresponding exemplary KPIs are depicted in Table 1.

FoA	**Exemplary KPI**
Station as a hub of intermodal mobility	Presence of active mobility infrastructure for access to the station (e.g. bike lanes, footpaths)
Station integration into the city (i.e. how to develop the surrounding urban areas)	Diversity of usage in the station and surrounding public spaces
Station as a circular economy hub (i.e. promoting recycling and use of materials)	Amount of food waste in shops and restaurants inside train stations
Station as an energy hub (e.g. examining how to produce energy locally)	Amount of energy produced in a sustainable way within the station itself (e.g. through regenerative breaking)
Station as a logistics hub (e.g. addressing last mile delivery)	Reduction in emissions and traffic congestion because of innovative last-mile delivery through railway stations
Resilience and green-blue infrastructure (UGI, addressing the potential of the station as a greening engine for the city)	Share of unsealed areas in the public spaces surrounding the stations
Station as a hub for socially inclusive services for citizens (addressing the need for proximity, safe and democratic spaces for exchange)	Availability of municipal social services within 15 minute walking distance from the station

Table 1. FoA of the draft model and corresponding KPIs

Since stakeholder collaboration is crucial in the context of railway station area development (Mouritz & Ainsworth, 2009; Stadler Benz & Stauffacher, 2023) a fact which has also been highlighted by participants in the expert workshops (Figure 2: phase 1, step B), we conceived the methodological toolkit as a 3rd core component of the draft model (c.f. Figure 3), which was utilized in the LLs process (second phase of the model development). As mentioned in the chapter “methods”, the toolkit provides a structured process for the identification and collaboration of relevant stakeholders. It consists of a workshop for proposing solutions regarding the sustainable transformation of railway stations and surrounding areas, as well as identifying the boundaries (e.g. institutional lock-ins) which can inhibit the solution application. Finally, the stakeholders using the toolkit are asked to identify the changes which are needed to overcome these boundaries. The validation process of the methodological toolkit in the second workshop round in phase 1 of the model development (Figure 2: phase 1, step C) led to productive discussions, where different points of view were discussed and compared. Furthermore, the focus on specific FoA and the steering of the discussion toward strategies/solutions and challenges of their implementation proved to be an apt way of developing tangible transformation pathways for railway stations, which correspond to the real conditions and problematics.

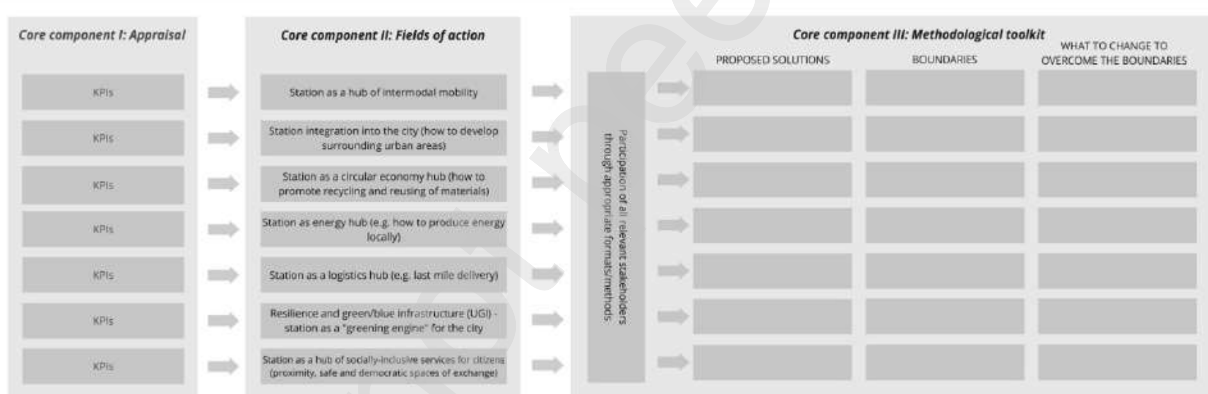

Figure 3: Draft model structure

Phase (2)

The results of phase (2) of the model development (LLs, c.f. Figure 2) are described in detail in *[YY]* and *[XZ]* (submitted for publication), however, for clarity, a brief overview is provided in this paper as well.

In the LL stakeholder workshops (Figure 2: phase 2, step A), the participants identified the FoA that were relevant to each LL using the methodological toolkit. For example, in the case of Milano Rogoredo station, the topic of energy was discussed in depth, and specific potentials were highlighted, such as utilizing parts of the station parking area for energy production and storage and implementation of mobility services for e-vehicles to be charged using local production of renewable energy. Calculations demonstrated that the implementation of PV in the whole parking area on roofs would allow energy generation capable of fueling both e-vehicles and the station building. The complex governance structure was identified as a boundary for the implementation of these solutions, while institutional partnerships and spatial optimization concepts were highlighted as possible solutions to overcome these problems.

Regarding the user profile identification (Figure 2: phase 2, step A), several recurring patterns emerged in the LLs. Public transport commuters, bicycle commuters, and car users consistently appeared as groups, with their behaviors and needs varied depending on the local dynamics of each station and thus some specific profiles also being unique to certain stations, highlighting the diverse commuting cultures. For instance, student commuters emerged as an important group at the Ottignies station, while the retiree user profile in Tomaszów-Mazowiecki station underscored the demographic structure of the station area.

The solutions developed in the ideation workshops (Figure 2: phase 2, step B) which were based on the user profiles highlighted similarities and differences across the LLs. Throughout all LLs, solutions pointing towards a differentiated use mix (e.g. everyday services in station area), urban sustainability (e.g. active mobility), user convenience (e.g. integrated ticketing options), and community engagement (e.g. use of station spaces by the local community) were prominent, highlighting the importance of turning stations into vibrant parts in the urban system. However, the specifics of implementation and the focus on individual commuter profiles differed significantly based on local needs and cultural contexts. For example, in Toulouse, bike infrastructure (e.g. parking, cycleways) solutions were explored in detail, reflecting the efforts of the city to encourage sustainable commuting, whereas in Dorfen the corridor between the city center and the railway station acted as a focus area for urban development due to the peripheral location of the station in relation to the city center.

Finally, placemaking actions across the LLs (Figure 2: phase 2, step C) effectively uncovered potentials of community engagement for envisioning sustainable futures in the selected railway station areas, as well as challenges for implementing participatory formats. Each intervention emphasized stakeholder and user participation, urban space use and educational aspects (*[YY]* & *[XZ]*, submitted for publication).

Phase (3)

The main result of phase (3) is the final model version (c.f. Figure 4), based on the draft model from phase (1) which was refined through the learnings of the LLs in phase (2) in a series of consortium workshops (c.f. Figure 2, phase 3). During the third phase of the model development, both the FoAs and KPIs underwent refinement to reflect the findings of the LLs. The FoA defined in the draft model proved to not adequately define the areas where action can be taken for the sustainable development of railway stations and surrounding areas according to phase 2 of the model development (LLs). For instance, very little potential has been exhibited in the topic of logistics and last-mile delivery, thus its explicit mention in the final model has been omitted. In contrast, mobility has been proven to play a central role, thus it has been elaborated with additional details such as active mobility and public transport. Furthermore, the draft model FoA of station integration into the city, resilience/green-blue infrastructure and socially-inclusive services/proximity showed synergies and interdependencies in the LLs, thus they were combined into one single FoA in the final model.

Ultimately, three main FoA were selected, each comprising three components (c.f. Table 2). The FoA (A) *sustainable mobility systems* comprises the components *mobility interfaces and infrastructures, active mobility,* and *public transport*, the FoA (B) *diverse and resilient spaces* consists of the components *mix of users, buildings and services, user perception and appropriation of space* and *nature-based solutions and urban health*, while FoA (C) *circular resource management* contains the components *goods*, *energy* and *business models*. Corresponding KPIs for each FoA component can be seen in Table 2.

The final model structure proposed to the consortium and IAB members received broad consensus. The structure was configured on two levels: the individual station level and an aggregated level. At the individual station level (c.f. Figure 4, lower part), the process of transforming a specific railway station is illustrated, in the form of a tool – a carryover effect from the highly applicable methodological toolkit from the draft model, but adjusted to fit the needs of stations that don’t have the means for a full LL process. Starting from an assessment of the current status of the station and station area, relevant stakeholders utilize workshop formats (such as the ones tested in the LLs) to primarily identify the relevant FoA and corresponding KPIs for the station. Participants in the model refinement workshops expressed the need for stakeholders to have the ability to individually select the importance of specific aspects of the FoA (and thus corresponding KPIs) for each station to which the model is applied. As a result, we structured the FoA into components, allowing stakeholders to measure the development of the stations solely through the KPIs relevant to those components. For example, stakeholders might opt to focus only on the *mobility interfaces and infrastructures* component of FoA *sustainable mobility systems* and consequently disregard the KPIs associated with components *public transport* and *active mobility*.

Once the relevant components of the FoA for the station have been identified, stakeholders are tasked with determining a specific transformation pathway for the station. They will do this by illustrating its current and desired future performance using FoA-specific KPIs in a radar chart (c.f. Figure 4), with one radar chart per FoA. Finally, based on the methodological toolkit from the draft model, stakeholders will identify solutions to overcome potential barriers that may hinder the station's development toward the desired objectives.

This process assists in the identification of sustainable transformation pathways for individual railway stations; however, it does not yet capture the transformation dynamics of all European railway stations. To address this problem, an aggregated level is introduced in the model (Figure 4, upper part). This level aims to integrate data collected in the future from the sustainable transformations of a large number of European railway stations, based on the individual station level, into a common knowledge base. By analyzing the data from multiple stations, one can define clusters of similar transformations, which will serve as common pathways for the transformation of railway stations across Europe.

FoA	Exemplary KPIs
A. Sustainable mobility systems	
Component 1: mobility interfaces and infrastructures	Presence of car/bike/ride sharing service and corresponding EV charging points
	Seamlessness of connection between mobility modes
	Amount of bicycle parking spaces
	Length of bicycle paths in the station catchment area
Component 2: active mobility	Percentage of users that walk or cycle to the station
	Transportation crashes and fatalities in the surrounding urban area and in the station
Component 3: public transport	Number of directions and frequency of train services /number of stopping trains
	Number of directions and frequency of bus, tram, underground/other transit modes
	Delays/waiting times
B. Diverse and resilient spaces	
Component 1: mix of users, buildings and services	Diversity of users and their activities in the station and station area
	Degree of land use mix in station area
	Amount and diversity of services in station area

		Average building density in station area
	Component 2: user perception and appropriation of space	perceived sense of security in and around the station
		Cognitive effort and successful orientation rate
		Existence/regular operation of participative processes for the design/use of the station and the surrounding area
	Component 3: nature-based solutions and urban health	Degree of Biodiversity around the station
		Degree of Urban Heat Island (UHI) Effect
		Green Space Coverage of station area
		Sustainable roof area use
C. Circular resource management		
	Component 1: energy	Amount of energy which is necessary for operating the station
		Share of renewable energy in the total energy consumption
		Share of energy produced at the station or by the railway company in total energy consumption
	Component 2: goods	Reuse rate of materials within station infrastructure projects
		Number of different recyclable and waste types collected within the station
		Amount of food waste produced in the station
	Component 3: business models	Business volumes of retail areas in and around the station
		Percentage of private financial resources supporting railway station area transformation projects
		Amount of knowledge-intensive firms in the station area

Table 2. FoA of the final model and corresponding KPIs

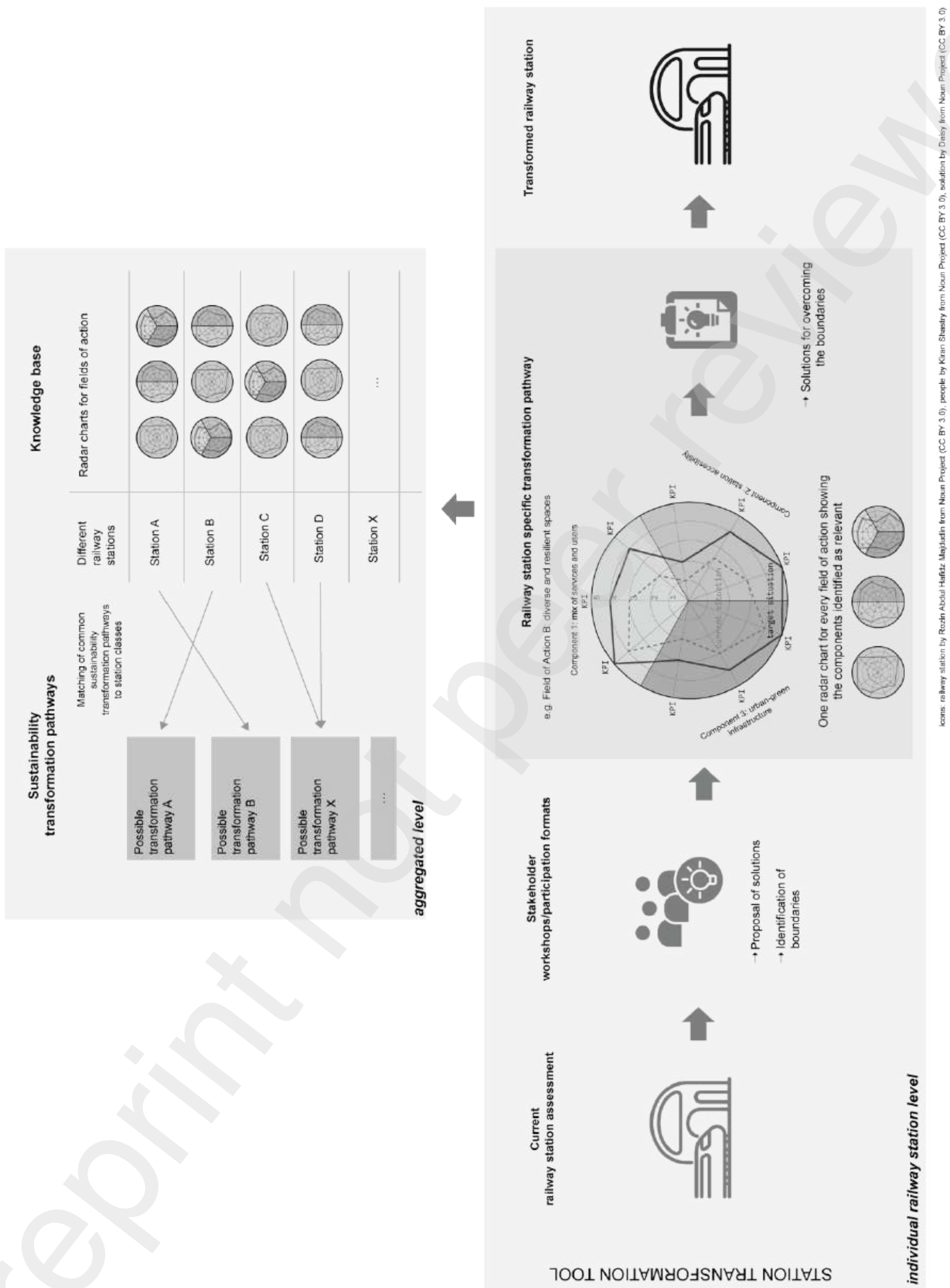

Figure 4: Final model structure

Discussion

In this paper, we aimed to describe and reflect on the development process for a model providing sustainable transformation pathways for European railway stations and station areas within the framework of TOD. The importance of this undertaking is highlighted by the role that railway stations can play in sustainable urban transformation in times of climate emergency (Dodman et al., 2022), as cores of TOD (Sun et al., 2024) and high-potential multifunctional elements in the urban fabric (Bertolini, 1996). Adding to the potential of TOD to foster sustainable urban environments solely through proximity to transit services, the proposed model uncovers new opportunities and challenges for TOD-induced sustainability transitions through the various FoA highlighted for the sustainable transformation of railway stations and surrounding areas.

Role of railway stations as pioneers of sustainable TOD

Through reviewing existing conceptual frameworks/models for railway stations and surrounding areas, as well as literature on TOD, we discovered that while several approaches describing the stations' transformation exist, none comprehensively explore their potential to contribute to sustainable TOD. Thus, in this paper, we outlined the process and methods we employed to develop a model that aims to define sustainable development pathways for European railway stations. Within this process, stations and their surrounding areas are considered integral parts of the transit-oriented urban system, with significant social, spatial, and functional implications. Thus, their transformation is considered only feasible through the appropriate stakeholder management approaches. Such approaches have been thoroughly tested during the model development phase and are now an integral part of the final model structure, guiding the station-specific transformation process. Within the TOD concept, railway stations serve as central hubs for organizing space based on a network of interconnected nodes (Banerjee, 2025; UIC Passenger Department, 2019). These nodes are characterized by high urban density, activity, and public transport accessibility, thereby reducing the reliance on car-based mobility and fostering vibrant communities (Salat & Ollivier, 2017). Thus, in their basic function alone, stations contribute to urban sustainability since urban density has a positive impact on public ridership (Pont et al., 2021) and rail transport is the least emissions-intensive passenger mode of motorized transport (UIC Sustainability Unit, 2024). However, some scholars suggest that ecological and environmental considerations are not adequately addressed in the TOD concept (Huang & Wey 2019) and that potential synergies exist by combining TOD with other aspects of sustainable urbanism (Cervero & Sullivan 2011), possibly resulting in a new TOD term iteration such as STOD (sustainable TOD).

The results of this study align with these claims and show that the attractiveness of railway stations and the ways they can contribute to sustainable urban futures go beyond their function as basic cores of TOD centered on mobility, thus introducing multiple sustainability perspectives to the TOD concept. The stations' central position in the urban fabric (Bertolini, 1996), their role in social human interaction (Bertolini, 1996), and their character as "a place of production and exchange of goods and services" (Spinosa, 2023, p. 2) allow for stations to acquire a variety of sustainable development potentials which are demonstrated by the FoA of the station model.

Some of these potentials have already been highlighted in the existing TOD literature (e.g. the encouragement of active mobility, Otsuka & Reeve, 2023), whereas others are novel and introduced in this paper (e.g. the development of nature-based urban solutions, c.f. next paragraph). By demonstrating how optimizing the stations' sustainable potential enhances their attractiveness, the model further reinforces the basic concept of TOD by promoting stations as cores of urban life, thus reducing car dependency (Cervero & Arrington, 2008), lowering emissions (Ashik et al., 2022), and encouraging efficient land use (Calthorpe, 2022).

Relation to existing railway station models and TOD literature

Though some of the methods used in the model development process relate to existing research methods (e.g. expert workshop formats used in the context of railway station development by Zemp et al. 2011), we deem a multi-phase approach (c.f. Figure 2) necessary to reflect the ever-increasing complexity of railway station areas. To date, no model explicitly includes sustainability as an aspect that is not constrained only to the dual role of the railway stations as mobility hubs and places in the city and thus as centers of TOD, as proposed in the NP model (Bertolini, 1999) and most of its variations. Rather, based on this research gap, our model proposes insights on a broader spectrum of potential roles that railway stations can play in the sustainable transit-oriented transformation of cities. Through the introduction of LLs and placemaking, the model development method further acknowledges the numerous possible spatial and social implications of railway station area transformation, particularly regarding the stakeholder and user perspective.

In comparison to the approaches discussed in the chapter "Literature Review," we observe similarities between our FoA and the topics highlighted as relevant for the development of stations in existing research. For example, railway station functions mentioned by Zemp (2011) such as *supporting transfer between modes of transport* relate to the FoA component *mobility interfaces and infrastructures.* Spinosa (2023) highlights the potential of energy production in stations which is included in our FoA component *energy;* the potential for railway stations to host cultural uses is mentioned by Juchelka

(2002) and is included in our FoA component *mix of users, buildings and services*. However, our model, while showing specific similarities to existing approaches, covers a wider array of sustainability aspects related to railway stations that have not been previously explored, such as ecology (e.g. through FoA component *nature-based solutions and urban health,* user perception (through the FoA user perception and appropriation of space) and circularity (through FoA *circular resource management*). Additionally, it brings together aspects that may have been mentioned in the literature before (such as urban design/walkability (Vale et al., 2018), energy (Spinosa, 2023), mobility (Bertolini, 1999), retail/leisure functions (Juchelka, 2002)) but have not been consolidated under a single framework. This integration allows for their implementation through a common transformation methodology.

Regarding further, not necessarily model-oriented TOD literature, we observe that the proposed FoA in our model align with sustainability aspects mentioned as important potentials for TOD (c.f. Cervero & Sullivan 2011, Huang & Wey 2019, Niu et al. 2021), such as circular waste management (related to the FoA *circular resource management*), energy sufficiency (related to FoA component *energy*) and the role of active and sharing mobility (*related to FoA* component *mobility interfaces and infrastructures*). ITDP (2017) further highlights the significance of diverse demographics (relates to the FoA component *mix of users, buildings and services),* safety of the active mobility network (relates to the FoA component *active mobility)*, as well as the importance of green spaces (relates to the FoA component *nature-based solutions and urban health).* Thus, the model validates the proposed aspects for sustainability in TOD, which have already been highlighted in literature, and adds more. It advocates for a multi-dimensional TOD that combines aspects of sustainability, spatial planning, and transport policies, thereby achieving social well-being in urban contexts.

Limitations

Nevertheless, we acknowledge that our model comes with limitations. For example, it has to be noted that the inclusive nature of the model, achieved by incorporating all relevant topics and ensuring its applicability to all European stations, results in the model becoming more generic in its characteristics and thus restricting the direct applicability of its components. This underscores the necessity of suitable stakeholder participation formats that can facilitate the conversion of the model guidelines into specific solutions tailored to each station and its unique context.

Additionally, the combination of normative elements like the FoA and KPIs with implementation methods that rely on descriptive processes in the model structure can result in complications in defining the nature of the model between the normative (i.e., what should the station of the future look like?) and descriptive spectrum (i.e., what does the station look like currently?), which are considered the primary types of model typologies (Beck & Jahn, 2021; Ronen & Sorter, 1974). Although the station model intends to establish sustainable transformation objectives, it also aims to accompany the station transformation through the offered methodology and suggested collaboration formats, thereby acting both normatively and descriptively. By explicitly modeling both the envisioned as well as the current state of KPIs within the FoA, the model structure effectively captures the complexities of station area transformation, but it compromises the alignment of its typology with conventional normative or descriptive model standards.

Considering model applicability, the results of the development process clearly demonstrate that developing sustainable transformation pathways for railway stations cannot be effectively achieved without working on the surrounding urban context. Although this fact has already been emphasized in TOD literature (e.g. Wenner & Thierstein, 2021) and was therefore anticipated, the ongoing debate about the definition of a station and its surrounding area directly impacts the model applicability spectrum. The literature review on station classification approaches (*[XX]* et al., under review) revealed significant discrepancies in how station areas are defined, with variations ranging from 500m (Papa et al., 2013) to 6km (Nigro et al., 2019). Furthermore, the LL results show that different solutions show sustainable transformation potentials on different scales. For example, providing bike-train intermodality depends not only on the characteristics of the station, but also on the overall bicycle infrastructure of the catchment area, whereas the adoption of circularity principles for station services spatially concentrates in the station building and immediate surroundings. These insights show that it makes little sense to define a specific application radius for the model at this stage. On the contrary, different scales should be considered for different solutions in TOD. However, the activation of the aggregated level of the model has the potential to prospectively support the identification of areas and scales that are relevant for railway station transformation.

Moving to the draft model validation process in the LLs (phase 2 of the model development), we noticed considerable challenges due to the small sample size of the LLs, which in turn limited the data produced and the information about their validity in different station contexts. Although the five LLs had been selected to represent diverse European stations and station areas – for instance, Toulouse Matabiau station is a central station in a metropolis and Dorfen station is a station on the outskirts of a small town – the literature review on station classification approaches (*[XX]* et al., under review) revealed that numerous distinct European station and station area types exist, exhibiting significant differences among each other. The limited results of the LLs combined with the complex landscape of European station types leads us to emphasize the need for collecting a considerably larger amount of data through the application of the station-specific part of the model in a large number of European stations as a future research step, thus activating the aggregated level of the model (c.f. Figure 4). The introduction of two distinct levels in the model structure (individual station level and aggregated level) may increase its complexity, yet it underscores the necessity for further research to gain a comprehensive understanding of the dynamics of sustainable transformation pathways for European railway stations.

Conclusion

Amid the climate emergency and the resulting need for the transformation of European cities (European Environment Agency, 2024), TOD) proves to be an effective concept for reducing CO2 emissions (Ashik et al., 2022), preventing urban sprawl (Calthorpe, 2022), and decreasing the reliance on automobiles (Cervero & Arrington, 2008), thereby freeing up spatial resources for more sustainable and ecological land use. However, it is being argued that the mere coordination of transport services and land-use (as the main idea of TOD) is not adequate in order to face the challenges of the climate emergency and that a further evolution of the TOD concept towards sustainability is needed (Huang & Wey 2019, Cervero & Sullivan 2011).

Railway stations and their surrounding areas, as centers of mobility and accessibility, serve as cores for TOD (UIC Passenger Department, 2019) and are generally significant elements in the urban fabric (Bertolini, 1996; Otsuka & Reeve, 2023); thus, they offer great opportunities for the development of a STOD paradigm, merging TOD with further sustainability potentials. Literature suggests that such a development could be grounded in a model for railway stations and surrounding areas (*[XX]* et al., under review; *[YY]* et al., *[year]*). Answering this call for a new model, in our paper, we highlight station areas as opportunity zones where urban planning can take place within the framework of TOD, but extended to include a sustainability dimension, contributing to social, environmental and economic sustainability.

Through examining the potentials of railway stations and surrounding areas in various formats such as expert workshops, fieldwork, user interviews and placemaking, we defined a variety of FoA and KPIs guiding and appraising the potential of stations for sustainable transformation as cores of TOD, which, together with stakeholder collaboration formats, are integral parts of the final model version. Though these different model aspects have been tested in real-life conditions, we identify a clear need for further research due to the limited number of LLs and resulting data. This can be achieved by applying the proposed transformation tool on an individual station level to a large number of European railway stations, enabling the collection of substantial data that can serve as a foundation for defining generic sustainable transformation pathways. However, the insights gained during the model development process, including the validation of the station-specific part of the model, already provide a solid tool for collaboratively exploring the potential of each station area. This tool can already be utilized to develop detailed plans for the development of individual railway stations and their surrounding areas within the framework of STOD. The data that can be collected through this process brings us closer to defining sustainable futures for European railway stations and, consequently, for sustainable cities.

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3 Outlook

The EU-wide model described in this deliverable aims to identify common sustainable transformation pathways for European railway stations and highlight their potential as drivers of sustainable urban futures. The model is part of a methodology designed to promote station transformation, enabling stations to assume this role. Its structure results from a lengthy participatory process involving stakeholders from academia, industry, and local communities, addressing the diversity of stations across Europe. While the model successfully illustrates how to develop detailed transformation plans for individual stations, it also highlights the need for further research due to the limited number of living labs (LLs) and corresponding data.

To address this, a second, aggregated level has been introduced in the model structure, serving as a bridge between RAIL4CITIES and future research projects. Within RAIL4CITIES, a robust transformative framework has been defined — including fields of action (FOA) and participatory formats — to guide station transformation. Future research will specify how data from multiple stations will be collected, aggregated, analyzed, and exploited to define broad transformation pathways. We suggest using standardized indicators across stations, common data collection protocols, and shared analysis tools to ensure comparability and consistency. As larger datasets become available, additions or modifications to the FOA may occur, reflecting the characteristics and peculiarities of station classes that may not have been researched within this project.

The model structure deliberately leaves certain aspects open, enabling station managers and local communities to develop context-specific station transformation approaches. For example, this is the case with the station catchment area, which is directly linked to the area relevant for the station's sustainable development. No single, predefined area is imposed within the model structure. However, scientific literature produced within the RAIL4CITIES project provides guidelines to assist and guide local communities and experts in addressing this topic. Specifically, Koulouris et al. (under review) emphasize that defining a suitable catchment area depends on the station's spatial context (urban/suburban/rural) — taking into account the differing first- and last-mile travel modes in suburban and rural areas compared with metropolitan/urban areas — the mode of transit (short-distance or long-distance services) – high-speed rail requires a larger catchment area than regional services –, and the specific transformative concepts and goals for each station. Using these factors, station managers and local communities can define catchment areas that are tailored precisely to their station context and function.

In this way, the model aims to provide a robust framework for guiding sustainable station transformation while also maintaining the flexibility and resources needed for stakeholders and local communities to adjust their station transformation pathways according to the specific characteristics of each station and its catchment area, as well as the specific needs of the local community.

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Pages in the pre-print	Alias	Source
1, 3, 5	[XY] project	RAIL4CITIES project
2, 3, 5, 24, 28	[YY] et al.	Lunardon, A., Vladimirova, D., & Boucsein, B. (2023). How railway stations can transform urban mobility and the public realm: The stakeholders' perspective. Journal of Urban Mobility, 3, 100047. https://doi.org/10.1016/j.urbmob.2023.100047
2, 4, 5, 8, 10, 23, 24, 28	[XX] et al.	Koulouris, S. N., Ruf, S., & Boucsein, B. Classifying European railway stations: A review. Manuscript under review.
5, 28	[XX], [YY], et al.	Koulouris, S. N., Lunardon, A., & Ruf, S. (2024). Developing and validating a model for railway stations as sustainable city promoters. Conference presentation and abstract at the Proximity Planning International Congress, Madrid, 288–290. https://doi.org/10.20868/UPM.book.82998
9, 10, 14, 15, 28	[YY] and [XZ]	Lunardon, A., & Boucsein, B. Developing a participatory methodology for transforming railway stations into vibrant urban hubs. Manuscript under review.

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