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Post-Industrial Adaptive Reuse in Poland as an Educational Template for Circular Economy in Architecture

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Abstract

Given the increasing global emphasis on implementing the circular economy (CE) across political, social, and economic domains, the application of its principles in architecture and construction is gaining strategic importance. This article explores the use of the 4R concept—reduce, reuse, recycle, recover—in the revitalization of post-industrial sites as a tool supporting the sustainable transformation of the built environment. In the theoretical section, a literature review is conducted to highlight the growing interest among researchers in CE-related issues and to outline the main directions of studies, including the integration of circular strategies with the challenges of adapting and sustainably transforming industrial heritage. The empirical section presents a qualitative comparative analysis of ten completed between 2014 and 2024 revitalization projects in Poland. It demonstrates how strategies of resource reduction, reuse, recycling, and recovery are implemented in design and construction practice. Particular attention is paid to the relationship between 4R principles and architectural quality, historical context, and investment goals. The findings indicate that the concept of 4R principles supports the reduction in environmental impact while creating new cultural value. This concept offers a viable tool for sustainable redevelopment of post-industrial buildings while preserving their industrial identity and heritage value.

Keywords: 4R; reuse; recycle; circular economy; sustainable design; post-industrial; revitalization; Poland

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1. Introduction

Adaptive reuse of post-industrial facilities has become a mainstream pathway to reduce the environmental burden of construction while unlocking underused urban assets. However, design teams still face fragmented guidance on how to operationalize circular strategies at the project scale. Post-industrial sites typically demand substantial interventions, such as structural alterations, removal or reconfiguration of industrial installations, remediation of residues, and re-plotting of external works, which can generate significant construction and demolition waste (CDW). Without a clear circular logic, such interventions risk contradicting sustainability aims even when they deliver urban and cultural benefits.

This study adopts a pragmatic 4R lens (Reduce, Reuse, Recycle, Recover) to structure decisions that limit waste and embodied impacts from the outset. The study analyses selected examples implemented in Poland in terms of the application of the 4R principles, which form the basis for reducing CDW. The aim of this paper is to identify methods and

models for the most effective implementation of these principles in construction, using the example of post-industrial revitalization projects; to determine the limitations and risks associated with their application; and to develop a general framework for the use of the 4R principles in architecture and construction. The purpose of the study is not to characterize the impact of revitalization on social, economic, or urban environments. The article is divided into four main parts: an introduction with a review of the literature and circular economy (CE) policies in construction; a description of the research methods and subject; case analyses regarding the implementation of 4R principles with a comparative summary; and a discussion presenting the potential, limitations, and framework for applying the 4R principles.

The need to apply sustainability principles already at the design stage of revitalization projects also follows from contemporary spatial development trends and the global policy agenda. In line with UNEP's forecast of a 60% expansion of the built environment by 2050 [1], risks of increased energy use and carbon footprint in the construction sector intensify—a sector that already accounts for 30–40% of energy consumption and 40% of the carbon footprint [2]. It is estimated that greater material recycling and improved materials management in construction could reduce CO_2 emissions on site by up to 80% [3], which would translate into a 5–12% reduction in EU greenhouse gas emissions and up to 37% at the global economic scale [4]. Consequently, reducing construction and demolition waste (CDW) and making better use of recycled materials aligns with the worldwide net-zero by 2050 objective under The Paris Agreement [5].

Moreover, the EU Waste Framework Directive [6] introduced a 70% recycling target for CDW by 2020 as a key step towards advancing the circular economy (CE). Nevertheless, it is estimated that only around 40% of construction waste is currently re-used or recycled [7]. The issue is significant, as CDW accounts for almost 38% of all waste generated in Europe and 12.3% in Poland [8]. In 2019, the European Green Deal further underscored the need to implement CE principles, particularly within resource-intensive sectors such as construction [9]. The Circular Economy Action Plan, currently being implemented across Europe, introduces a suite of measures aimed at increasing the recovery of materials and energy from waste, including CDW [10]. This strategy places particular emphasis on the construction sector's resource intensity, noting that it consumes nearly 50% of resources and generates an estimated 35–40% of all waste in the EU [7,10]. European regulations on construction products also state that buildings should ensure the sustainable use of natural resources, including the re-use or recycling of buildings, components or construction materials, as well as the durability of the buildings themselves [11]. One means of reducing CDW and greenhouse gas emissions is to limit embodied-carbon emissions [12–14].

The United Nations, in its recent report [15], indicates the directions in which the construction industry should evolve in order to reduce its negative environmental impact. One of the key elements of this policy is the implementation of the CE in construction, which is based, among others, on introducing systems for managing recyclable building materials, designing for reuse, and applying durable materials. The report also emphasizes the necessity of adapting existing buildings, which can reduce the carbon footprint by approximately 40–50% compared to demolition and new construction. Furthermore, it presents a global tool for assessing circularity in the construction industry, highlighting not only material-related solutions but also the use of existing urban and built fabric as a factor positively influencing the application of CE principles [16]. The first impulses for the development of the circular economy concept emerged in the United States with the publication of Silent Spring (1962) by Rachel Carson [17]. Although the book did not directly present CE principles, it became one of the key inspirations for later ideas on sustainable resource and waste management [18]. In the 1970s, ecological thought

was further developed by Barry Commoner, who in The Closing Circle (1971) formulated four laws of ecology, emphasizing the interdependence between natural systems and human activity [19]. His postulates indirectly influenced growing public awareness and subsequent legal regulations in waste management, such as the Resource Conservation and Recovery Act (RCRA) adopted in the U.S. in 1976 [20]. In the 1980s, developed countries began introducing selective waste collection systems and educational campaigns aimed at increasing social awareness of responsible material management. Jawahir and Bradley point out that this period saw the formulation of the 1R principle (reduce), which became particularly important in the context of lean manufacturing and laid the foundation for the 3R principles developed in the 1990s [21]. During this time, the global crisis of overproduction and increasing waste volumes intensified, leading to numerous policy initiatives in industrialized countries such as Germany and China [22]. One of the core concepts applied in CE became the 3R principle (reduce, reuse, recycle), which was later extended by additional "re-strategies", resulting in broader frameworks such as 4R, 6R, and even 10R [18,21].

In response to global environmental challenges, concepts derived from the CE—such as 3R or 4R—are beginning to play an increasingly important role in the construction management. Particularly relevant is the 4R approach: reduce, reuse, recycle, and recover, which—although originally developed within the field of waste management—is now being more widely applied in sustainable design. The reduce principle in construction may be understood as limiting construction and demolition waste (CDW) by right-sizing material use, curbing demolitions, and minimizing transformations to existing fabric. The next of the 4R principles—re-use—should be interpreted as the utilization of materials, buildings, or their parts without additional energy input or material reprocessing [23], which most often means retaining the original function of a building element without replacement. In contrast to re-use, recycle requires energy input and processing of an element so that it can be applied in a new form [23,24]. Recover, in the context of construction processes, denotes the recovery of value—economic or spatial—from materials or assets that no longer fulfill their original role.

2. Literature Review

In recent years there has been a marked increase in publications addressing the circular economy (CE), including studies directly concerned with the 3R/4R principles. An increasing number of works focus on material and energy recovery as a crucial component of sustainable design. This body of literature typically examines three key aspects of waste management in construction:

- Recycling or re-use of demolition-derived materials;
- The use or processing of waste (not limited to construction waste) as building materials within the construction industry;
- Assessment of the phenomenon and methodologies for implementing circular-economy strategies in construction.

The second research strand considered in the literature review concerns the revitalization of post-industrial facilities, with particular attention to the Polish literature and environmental determinants. The scope and topics of the literature review are presented in Figure 1. Architectural magazines (both print and online editions) were used in this study as valuable sources of up-to-date information, alongside scientific publications presenting the current state of knowledge subject to verification.

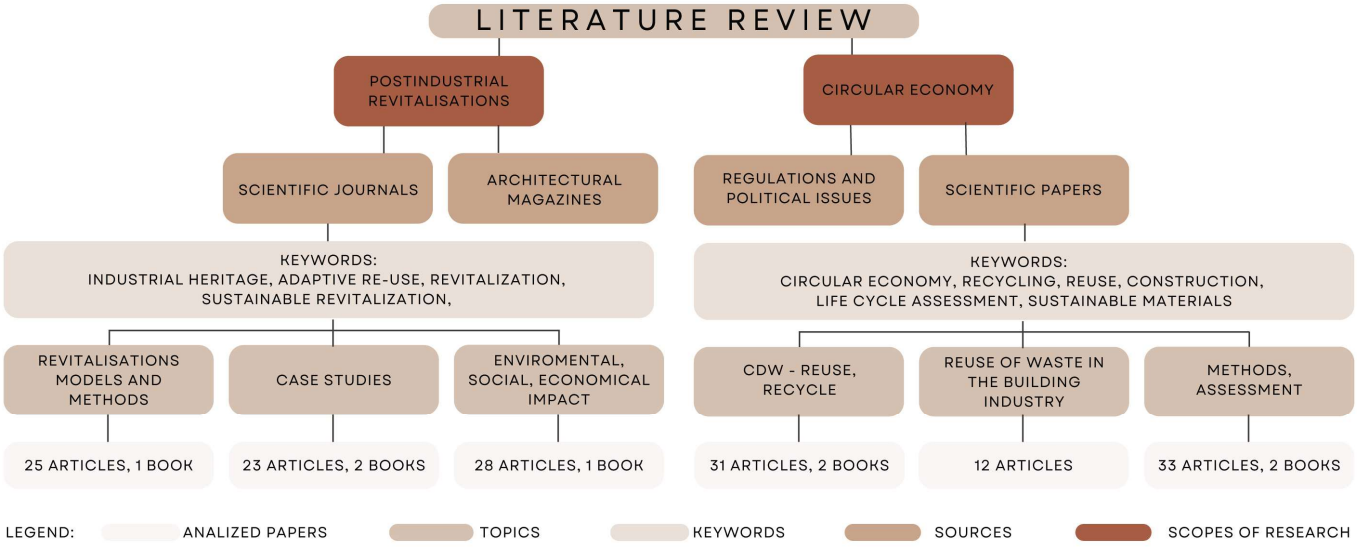


Figure 1. Literature review chart (authors, 2025).

2.1. Circular Economy in Construction Sector—Recycling of Building Materials

One of the most valuable sources addressing general CE issues in construction is the *Manual of Recycling*, which presents a range of practical examples of recycling in the building sector as well as useful methods for calculating recycling costs and its environmental impacts [23]. An equally important contribution is the work by Stricker et al. [25], which outlines opportunities for applying CE in architecture and their implications for environmental protection. At the intersection of CE application and the revitalization of industrial facilities are case studies of the K.118 project in Switzerland: Catherine De Wolf et al. characterize the environmental impacts of a CE-based realization using K.118 as the exemplar [26], while Stricker et al. provide a detailed study highlighting numerous instances of recycling and re-use within the same project [27]. A broader survey of CE opportunities in architecture and construction is offered by Kapica et al. [28], who present multiple examples of recycling in the sector and propose a system intended to facilitate CE implementation within the construction industry.

Researchers addressing the issues of recycling and reuse of building materials pay particular attention to the application of concrete in construction, both as structural components [29] and as aggregate used for sub-base layers or as recycled content in new concrete mixes [24,30]. Equally important is the research concerning the potential reuse of steel and timber elements, which highlights their considerable potential for reapplication in construction, either as structural elements or as finishing components [31–34].

2.2. Assessment and Implementation Methodology of the Circular Economy in the Construction Sector

A valuable study on waste management methods is the work of Huanyu Wu et al., in which the authors review various waste management methodologies and highlight the significant impact that effective waste management in the construction sector can have on the environment, economy, and society [35]. Their findings indicate the substantial effect that CE implementation can have on reducing the carbon footprint of construction processes. Julia Nussholz, in turn, investigates the potential reduction in CO_2 emissions depending on the adopted design and construction methods, based on the analysis of 65 building projects [12].

Researchers have also undertaken efforts to assess the economic aspects of construction waste recycling. Francisco et al. present a simple tool for calculating the amount of waste

generated and its potential for reuse [36]. A particularly important comparison of energy savings is provided by Ng and Chau, who indicate that recycling walls, ceilings, and finishes can yield energy savings of nearly 80%. However, in the case of window and door joinery, material reuse proves significantly more beneficial than recycling [37]. Simi-larly, Ostręga et al., in a comparative analysis of adaptive reuse versus demolition and new construction of former mining facilities in the Małopolska region, demonstrate substantial economic, environmental, and social benefits associated with revitalization models based on the reuse of industrial buildings [38].

An important research direction relating both to sustainable construction and to the adaptive reuse of historic buildings includes studies analyzing the environmental impact of reusing existing structures. Ali and Ahmed, using the LEED (Leadership in Energy and Environmental Design) assessment system, examined the adaptation of two different buildings that also incorporated recycled materials. Both projects achieved a Silver certification in the LEED system, obtaining particularly high scores in the Energy and Atmosphere and Materials and Resources categories [39].

A valuable greenhouse gas emission analysis was conducted by Kyaw et al., who compared the adaptation of former warehouse buildings with their demolition and recon-struction [40] for new storage and office use. According to their findings, adaptive reuse reduced GHG emissions by more than 80% compared to demolition scenarios. Similar conclusions were reached by Hu and Świerzewski, who analyzed the adaptive reuse poten-tial of a school building constructed in 1906 [41]. Their study demonstrated that reusing existing structures reduces global warming potential by 82%, smog-forming emissions by 51%, and acidification factors by 27%. Zimmermann et al. likewise observed, when analyzing building renovation standards and strategies in three Scandinavian countries, that renovation generally outperforms demolition and new construction, although they did not provide specific quantitative data [42].

A different perspective is offered by Huuhka et al., who performed a long-term comparative analysis between renovation and new construction on the same site [43]. The authors note that the potential environmental benefits of advanced technologies in new buildings begin to offset the impacts of renovation only after approximately 30 years of operation.

2.3. The Use of Waste in Construction Sector

In the context of the Circular Economy, researchers are also exploring the potential of using various types of waste as building materials or additives in construction. Some studies focus on methods for managing waste and reusing materials in the construction industry [44,45]. Wahid Ferdous et al. present a wide range of possibilities for using waste materials such as rubber, glass, and others, emphasizing that sustainable actions in waste management not only reduce unhealthy landfills but also contribute to job creation [46].

2.4. The "R" Principles in CE

The broad spectrum of ten "R" principles in the circular economy is presented by Morseletto [47], with their use and definition contingent on the desired outcome. These principles address the economy at large rather than the construction sector specifically, where several "R" applications tend to overlap in meaning. For the built environment, a more tailored characterization is proposed by Jawahir and Bradley through the 6R framework spanning the full life cycle [21], although even in their interpretation certain notions blur when applied to construction. The most pertinent and accurate account is offered by Huang et al. [48], who, drawing on studies and examples from China, delineate the 3R principles and identify the opportunities and barriers to their implementation. All

researchers agree that the most critical component within the CE framework is the principle of reduce.

2.5. Revitalisation of Industrial Sites: A Review of the Literature

The scope of research on the revitalization of post-industrial facilities is very broad. Among studies on this topic, three principal strands can be distinguished: theoretical issues and models of revitalization processes; case studies and their social or financial impacts; and questions related to sustainable design. A valuable contribution addressing revitalization is the work by Maciejewska and Turek [49], which, in addition to analyzing European cases, sets out design-and-delivery guidelines and indicates methods of action to be undertaken within revitalization processes. An interesting account of differentiated process models is provided by Wowrzeczka [50], who—using power plants as examples—characterizes three baseline approaches to revitalization: ecological, commercial and conservation-focused. Baborska-Narożny likewise, in a concise yet substantive paper [51], identifies five principal models of post-industrial revitalization, dependent on the intended objectives. In the context of non-commercial schemes dedicated to the arts, Pieczka and Wowrzeczka identify five distinct strategies on the basis of an in-depth analysis of art-related projects delivered within revitalized post-industrial structures [52]. From the perspective of both theory and practice, Lenartowicz and Ostręga [53] also offer a valuable study, drawing attention to risks associated with revitalization processes such as legislative constraints and incomplete technical or survey documentation of buildings.

Many scholars of post-industrial revitalization also emphasize the need to balance commercial and social considerations during adaptation. This is particularly important in Poland, whereas Dudzińska-Jarmolińska notes—commercial revitalization of post-industrial sites has a markedly greater share than in other European countries [54]. Grzelak and Pielasiak highlight risks associated with the commercialization of such facilities and their financial performance, arising from spatial conflicts and an improper definition of social requirements [55]. A valuable contribution is also offered by Misiuk [56], who provides guidelines for delivering commercial schemes within post-industrial buildings, illustrated by the case of a factory in Białystok. Equally important are studies addressing the social dimensions of revitalization: most researchers identify positive outcomes for local communities and local economies [57–60].

In academic studies concerning the revitalization of post-industrial buildings and areas, the aspect of sustainable development is particularly significant [58]. Contemporary spatial and functional demands call for environmentally responsible solutions and the integration of new technologies and building functions that address present societal needs [61]. Echoing this direction, Szewczyk-Świątek et al. show—through analyses of post-mining areas and research by design on the Brzeszcze mine—that applying circular-economy principles can guide the retention or transformation of post-industrial landscapes [62]. Within this agenda, Iodice and De Toro argue that a circular-economy–driven revitalization model can both reduce waste and improve the energy performance of refurbished structures while reinforcing the cultural identity of place [63]. Such interventions, however, must safeguard the historical and esthetic values of industrial heritage, as Trifa cautions [64]. Empirical evidence from surveys and case studies similarly indicates that adapting post-industrial buildings while retaining their distinctive identity supports sustainable urban development across ecological, social, and economic dimensions [65,66].

2.6. Revitalisation and Adaptive Reuse of Industrial Sites in the Western Europe

The issue of revitalizing degraded post-industrial areas is frequently addressed in Western Europe. Ikiz Kaya et al., in their study of 53 Dutch adaptive reuse projects, demon-

strate that adaptive reuse of heritage buildings serves as a genuine driver of the circular economy, as it enables the preservation of existing resources and embodied energy while maintaining the cultural values of the buildings [67]. The proposed circularity assessment framework integrates these two dimensions by measuring the preservation of cultural values, the circularity of the intervention itself, and the post-adaptation performance outcomes. This provides a basis for a comparable "circular + heritage" evaluation of projects. Survey results among stakeholders indicate a high appreciation for the protection of heritage values, while also showing that a greater degree of circularity in interventions (e.g., reuse and limitation of new materials) contributes to improved functional outcomes after adaptation [67].

Arfa et al. verify a model of the adaptive reuse process for heritage buildings based on four Dutch case studies [68], demonstrating that the effectiveness of AR results from a non-linear workflow and recurrent loops of design decisions. The authors point out that it is precisely the design decisions—from the early diagnosis of heritage values and identification of elements worth preserving, through stakeholder collaboration, to flexible implementation—that determine the scale of reuse and the reduction in new material inputs (and thus the circularity of the intervention). The model provides a clear map of key moments at which the designer can "close the loop" (e.g., by maintaining the existing structure, performing selective demolition, or preparing elements for disassembly), and then link them with circular economy practices such as material passports and design for disassembly during the implementation phase. As a result, AR becomes a tool not only for preserving cultural values but also for reducing CDW and the demand for new raw materials [68].

The transformation of Strijp-S, the former Philips industrial complex, into a mixed-use creative and residential district analyzed by Barbalis and Curulli [69], also provides valuable insights. The redevelopment was based on the selective preservation and adaptation of approximately 120,000 m^2 of heritage buildings, with the principles for transforming existing halls (such as podiums and roofs) embedded directly into the masterplan. This approach made the reuse of structural frameworks a key driver of sustainability, even though the preservation of industrial machinery was not emphasized.

In Germany—particularly in the Ruhr region—revitalization is strongly oriented towards environmental regeneration: from the IBA Emscher Park programmed to the long-term renaturation of the Emscher river system, which transformed a former sewage canal into a "blue" ecological and recreational corridor for the entire metropolitan area [70–72]. At the same time, the preservation and adaptation of industrial heritage have reinforced the social and economic impact of these transformations: the Zollverein UNESCO site recorded approximately 1.5 million visitors annually between 2011 and 2016, becoming the region's most visited attraction [73]. This intertwining of environmental restoration and heritage reuse has created a distinct place identity and has significantly supported both tourism and the local economy [71–73]. As a result, the "green regeneration + heritage reuse" approach fosters not only ecological resilience but also the touristic and cultural attractiveness of the region [70–73].

At the architectural and landscape scale, the principles of reuse and recycle are evident in flagship projects. Landschaftspark Duisburg-Nord makes use of existing materials and structural elements in transforming a former steelworks into a public park, while remaining an intensively visited site—thus confirming the synergy between environment, culture, and tourism [74,75]. Similarly, Phoenix-See in Dortmund illustrates how the reclamation and conversion of former steel industry sites can combine a new urban program with environmental quality improvement, aligning with the logic of reducing CDW and emissions through preservation or reconstruction of resources [76]. Such examples operationalize the

CE within revitalization, prioritizing structural retention, selective demolition, and on-site recycling over the linear "demolish and dispose" approach [70,74,76]. As a result, the flows of primary materials and the environmental footprint of interventions are significantly reduced [70,74].

German cities are also developing CE tools and policies that translate these principles to a systemic scale. The material resource cadastre for the Rhine–Ruhr metropolis (as discussed in *Buildings*) demonstrates how mapping 16 material fractions within the built environment can support planning for recovery and reuse throughout the revitalization cycle [77]. Berlin has adopted 2030 targets, including achieving 64% recycling of construction waste and the use of approximately 400,000 tonnes of recycled concrete and gypsum in construction—supported by design for disassembly practices and secondary material loops [75,78]. Initiatives such as the Haus der Materialisierung provide an infrastructure for reusing components and materials in regeneration projects, connecting architects, contractors, and secondary material operators [73]. It is precisely this metric infrastructure (cadastres, material passports) and policy framework ("zero waste" strategies) that enable the integration of heritage reuse with measurable CE outcomes in revitalization processes [73,75,77,78].

3. Methods

The study selected projects delivered in Poland—irrespective of region of Poland—completed between 2014 and 2024 (a ten-year period). A further primary selection criterion was the recognizability of the schemes, chiefly evidenced by publications in the professional (architectural) press. This criterion was adopted owing to the opinion-forming role of such projects, which establish trends and set directions for the further development of architecture in comparable undertakings. Selected projects are presented in Table 1.

Table 1. Summary of basic data on analyzed post-industrial revitalization in Poland [79–91].

Revitalized Post-Industrial Complex	Nature/Adaptive Reuse Functions	Area (ha)/Net Floor Area (m^2)	Style	Location in the City	Author of the Revitalization Project
Wrocław Brewery	Commercial/Mixed-use: residential with services	3.9/48,546 [79]	Neogothic	Rims of the Downtown	SRDK Architekci studio
"Mamut" Bakery in Wrocław	Commercial/ Hotel, dormitory, restaurant	0.93 [80]/ 45,300 [81]	Art-Deco	City Center	Grupa 5 Architekci
Old Coal Mine in Wałbrzych	Public/Museum, Municipal Cultural Centre, Hotel,	4.45/26,270 [82]	Eclecticism	Rims of the city	Nizio Design International, WPA—Wilisowski Pracownia Projektowa, PAS Projekt Archi Studio
Goetz Brewery in Kraków	Commercial/Mixed-use: residential with services: hotel, offices, retail, gastronomy	2.05 [83]/ 31,000 [84]	Eclecticism	City Center	MOFO Architekci

Table 1. *Cont.*

Revitalized Post-Industrial Complex	Nature/Adaptive Reuse Functions	Area (ha)/Net Floor Area (m^2)	Style	Location in the City	Author of the Revitalization Project
Brewery in Ostrowiec Świętokrzyski	Public/Municipal Cultural Centre, Library, cinema, gastronomy	0.68/5514 [85]	Historicism	City Center	Dresler Studio Architektura i Urbanistyka
Powiśle Power Plant in Warsaw	Commercial/Mixed-use: residential with services: hotel, offices, retail, gastronomy	2.7 [86]/ 73,008 [87]	Historicism	Rims of the City Center	APA Wojciechowski, Belotto Design
Norblin Factory in Warsaw	Commercial/services: offices, retail, gastronomy	2/65,000 [88]	Eclecticism	Rims of the City Center/downtown	PRC Architekci
"Koneser" Vodka Distilleryin Warsaw	Commercial/mixed-use: cultural —galleries, museum, offices, retail	4.8/100,311 [89]	Neo-Renaissance	Rims of the City Center	Juvenes Projekt, Are, Bulanda & Mucha Architekci
Warsaw Brewery	Commercial/Mixed-use: residential with services: offices, gastronomy	4.2/125,128 [90]	Eclecticism	Rims of the City Center/ downtown	JEMS Architekci
Żnin Sugar Factory	Commercial/Hotel, gastronomy conference center, recreational, wellness	3.5/35,000 [91]	Neogothic	Rims of the City Center	Bulak Projekt, Marek Bulak and Piotr Grochowski

The research was grounded in traditional methods used in the discipline of Architecture (Figure 2). First, a review of scholarly and popular-scientific literature was conducted, primarily to select the objects for study. Drawing on this literature, research criteria were also defined in the field of sustainable design, namely, the 4R principles and their application in the construction sector. Subsequently, field surveys were undertaken to identify which 4R principles were implemented and to what extent in the analyzed projects. On this basis, a comparative analysis was carried out across the cases, and good practices in sustainable design.

In analyzing the implementation of the 4R principles in the examined revitalization projects, the definitions proposed by Huang et al. [48], Stricker [25], and further refined by De Wolf [26] were adopted. The *reduce* component refers to the limitation of CDW through the reuse of existing materials and the minimization of interference with the existing built fabric. The next component, *reuse*, is defined as the repeated use of an element without significant additional processing. It is primarily understood as the reuse of a given element in the same or a similar function. In contrast, *recycle* requires further processing of the material in order to enable its use in a new or similar function to the original one. The final component, *recover*, refers to the retrieval of economic or cultural values from spaces or buildings that no longer serve their original purpose. The assessment of the occurrence of these principles was based on quantitative indicators, namely, the frequency of their application within the revitalized spaces.

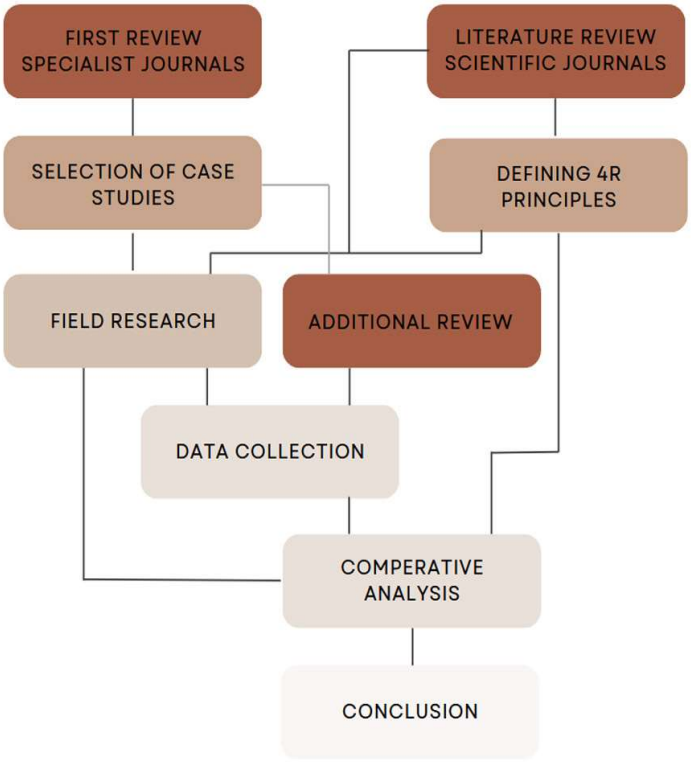


Figure 2. Research methods chart (authors, 2025).

Due to the overlapping nature of various concepts used in the literature, a distinction was made between the definitions of revitalization methods. According to the UNESCO Recommendation on the Historic Urban Landscape [92], revitalization is understood as a process of renewing degraded urban or historic areas through the preservation of their cultural values while introducing new functions that meet the needs of contemporary society. Within this framework, adaptive reuse—defined by the ICOMOS Burra Charter [93] as "the process of adapting buildings for new uses while retaining their historic features and values"—represents one of the key architectural strategies supporting revitalization processes. In architectural terms, adaptive reuse involves modifying existing buildings to accommodate new functions other than those for which they were originally designed, while maintaining their cultural significance. However, adaptive reuse is not always possible. In many post-industrial contexts, the degree of structural degradation, contamination, or loss of material integrity prevents the direct adaptation of existing fabric. In such cases, revitalization may require partial reconstruction, selective preservation, or even reinterpretation of industrial heritage elements.

4. Results

4.1. Case Studies

4.1.1. Wrocław Brewery

One example of a project that attempts to implement some of the 4R principles is the revitalization of the Wrocław Brewery, completed in 2023 (Figure 3) [94]. All preserved buildings of the former brewery were retained, and particular attention was paid to minimizing interventions in the historical building fabric. Consequently, the amount of demolition waste was significantly reduced. Elements of industrial machinery and structural components were reused as exhibits—artifacts referencing the site's former identity. An example includes historic wind braces, which were displayed on new buildings constructed as part of the development. In the residents' club, cast iron floor plates from

the production hall were reused as wall finishes [94]. Former iron trusses and columns from the industrial buildings were repurposed as trellises for climbing greenery (Figure 3). In addition, iron components from buildings and technical equipment were reused as elements of small architecture (Figure 4). As in other analyzed projects, new development was also introduced here, with some buildings reconstructing historical, now-absent structures. During the pre-design phase, a digital inventory using 3D scanning of preserved structures was carried out [95]. The use of advanced surveying technologies contributed to a more accurate preservation of the existing building fabric.



Figure 3. An example of applying 4R principles in the revitalization of Wrocław Brewery: (**a**) *reuse*—use of cast iron columns from a former stable roof as supports for a balcony; (**b**) *reuse*—reuse of historic wind braces as decorative elements on new buildings; (**c**) *recycle*—repurposed cast iron structures used as trellises for climbing plants; (**d**) *recover*—land and building recovery, including through urban infill. Source: author's photo (May 2025).



Figure 4. Wrocław Brewery—recycling of cast iron building components and industrial machinery into small architectural elements: (**a**) wheel used as a bench backrest; (**b**) cast iron bicycle rack; (**c**) column heads repurposed as bench legs. Source: author's photo (May 2025).

4.1.2. "Mamut" Bakery in Wrocław

The redevelopment of the Mamut Bakery in Wrocław posed a significant challenge in adapting existing post-industrial structures to new functions—a private student residence

combined with a hotel [96,97]. Since its construction, the complex had undergone numerous transformations, which necessitated a design approach aimed at restoring the original stylistic features of the preserved buildings [98]. Unfortunately, no technological equipment from the bakery had survived; only the basic spatial layout and characteristic ceramic finishes remained [96,98].

The project incorporated the specific features of the existing building fabric into the functional program. Large, poorly lit spaces on the lower floors—due to the presence of small windows—were designated for communal areas, while the better-lit spaces on the upper three floors were used for hotel rooms and short-term rentals [66]. A key feature of the design was the retention of much of the building's structural framework, with local reinforcements, as well as the preservation of glazed tiles and terrazzo floors reinforced with cast iron within the interiors (Figure 5a) [68]. These measures helped to reduce construction waste by minimizing interventions into the existing structure. Consequently, the potential for reuse of demolition materials was limited—although it should be noted that the circulation areas were significantly remodeled.



(**a**) (**b**) (**c**)

Figure 5. Example of applying 4R principles in the revitalization of the Mamut Bakery in Wrocław: (**a**) *reduce*—reduction in construction waste through the use of existing ceramic tiles and terrazzo flooring reinforced with a cast iron grate; (**b**) *reuse*—use of cast iron columns as decorative relics; (**c**) *recover*—recovery of urban space and historic building fabric, including the original bakery and its later extensions. Source: author's photo (May 2025).

The principle of reuse is present in isolated architectural elements, such as a hoist motor and cast iron columns, retained as relics of the building's industrial past (Figure 5b). The Mamut Bakery project also utilized modern inventory techniques, including 3D scanning and the creation of a digital twin of the building, which enabled more accurate assessment of investment potential and further reduced the need for structural interventions [96].

4.1.3. The Old Mine (Stara Kopalnia) in Wałbrzych

The Old Mine in Wałbrzych (Stara Kopalnia) serves as an example of a non-commercial revitalization project funded with public resources, resulting in the creation of a cultural institution—the Centre for Science and Art, a mining museum. In this project, the application of the 4R principles was successfully integrated into the basic functional program (Figure 6).

One of the most important measures was the reduction in demolition (Figure 6a). Only two buildings were dismantled: the former cooling tower, which was reconstructed as a viewing tower, and the canteen building, replaced by a steel "gateway" marking the entrance plaza to the entire site. Due to the vast size of the complex and available funding, some structures—such as the coal washing facility—were not yet revitalized. These buildings were not demolished and are planned for future redevelopment into additional museum spaces [84].



(**a**) (**b**) (**c**)

Figure 6. Examples of applying 4R principles in the revitalization of the Old Mine (Stara Kopalnia) in Wałbrzych: (**a**) *reduce*—minimization of demolition through preservation of buildings for future adaptation; (**b**) *reuse*—use of old machinery and equipment parts as exhibition elements; (**c**) *recover*—full recovery of post-mining areas and facilities for cultural center functions. Source: author's photo (May 2025).

One of the key features that determined the adaptation of the mine for museum and cultural purposes was the preserved condition of the mining equipment and machinery, which represent the commonly used extraction techniques and technologies from the mid-19th century onwards [99]. Numerous remnants of these machines and devices used in coal mining were repurposed as museum exhibits. The main operational equipment of the mine—such as the engine, hoist, and the shaft lift—have been preserved in their original state. In the open spaces between the buildings, additional elements of machinery and tools for coal extraction and transport have been arranged (Figure 6b). This use of the original equipment exemplifies the *reuse* of various elements from the site's industrial past.

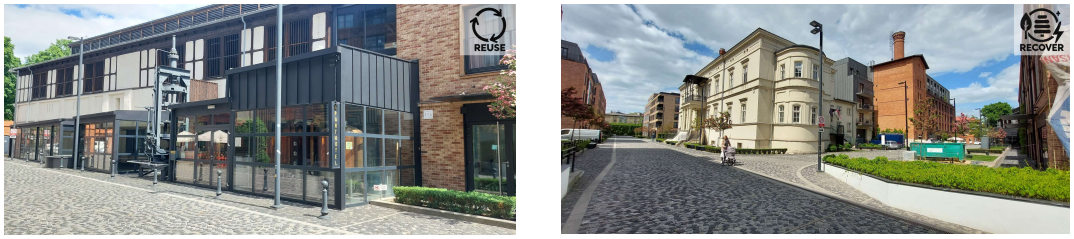
The case of the "Old Mine" in Wałbrzych presents an excellent example of how former industrial heritage can be adapted for public purposes. The use of numerous remnants of machinery and buildings for exhibition purposes corresponds closely with the assumptions of the 4R principles. It is also worth noting that the intangible heritage of industrial culture has been preserved—tour guides are former mine employees who, in addition to presenting the exhibits, share stories about the everyday life of the site, its operation, and the culture of work.

4.1.4. The Goetz Brewery in Kraków

The Goetz Brewery on Lubicz Street in Kraków serves as an example of a commercial post-industrial revitalization project. Originally established in the mid-19th century, the site underwent significant transformations over nearly 150 years of production. Due to the poor technical condition and extensive degradation of the structures and spaces, a decision was made—following consultation with the heritage conservator—to adapt six of the most historically valuable buildings and to demolish the remaining ones, which primarily consisted of extensions built in the 1970s [100]. Only buildings listed in the heritage register were preserved: the palace (administrative building), the former malt house, a staircase tower with a chimney, sections of the perimeter wall, as well as the refrigeration engine room, boiler house, and chimney [101].

Despite the careful adaptation of the preserved buildings and the new architecture referencing industrial features, the project did not incorporate methods aligned with the 4R principles. The reuse of elements such as brewing vats, barrels, and fragments of technical infrastructure (Figure 7a) was limited to isolated decorative gestures—serving more as symbolic references to the site's industrial heritage than as functional applications. There is also no evidence of recycled building materials in this project. As such, the revitalization of the Goetz Brewery does not engage with the 4R principles, with the only possible references

being the general notions of recovering urban land and the reuse of selected buildings (Figure 7b).



(**a**) (**b**)

Figure 7. Example of applying 4R principles in the revitalization of the Goetz Brewery in Kraków: (**a**) *reuse*—use of industrial equipment as relics; (**b**) *recover*—recovery of post-industrial space and buildings in the city center through redevelopment and the construction of new residential and service buildings. Source: author's photo (May 2025).

4.1.5. Brewery in Ostrowiec Świętokrzyski

The revitalization of the former brewery complex in Ostrowiec Świętokrzyski is another example of a publicly funded investment project, in which a cultural center was established within the post-industrial site. Despite the cessation of production in 1970, the facility continued to function as a warehouse [87], and between 1986 and 1995 it housed the Municipal Cultural Centre [102].

In this revitalization, only the most fundamental principles of post-industrial regeneration are evident—namely *reuse* and *recover* (Figure 8). A notable feature indicating a degree of sustainable development is the limited scope of demolitions, which aligns with the application of the *reduce* principle.



(**a**) (**b**)

Figure 8. Example of applying 4R principles in the revitalization of the brewery complex in Ostrowiec Świętokrzyski: (**a**) *reuse*—use of cast iron columns with integrated fire protection; (**b**) *recover*—recovery of the site and buildings for cultural purposes. Source: author's photo (May 2025).

4.1.6. Powiśle Power Plant in Warsaw

The Powiśle Power Plant is located in the former workers' district of Warsaw, now absorbed into the city center. The revitalization process for this area had already begun at the turn of the 20th and 21st centuries, with the construction of public utility buildings such as the University Library and the Copernicus Science Centre. The improvement in the quality of the surrounding space significantly increased the investment attractiveness of the power plant site itself. The revitalization of the power plant, completed in 2020, represents

a fully commercial project [50]. It was based on the redevelopment and adaptation of the boiler house and turbine hall into a shopping center, as well as the adaptation of the transformer station and caisson into a restaurant. A number of new residential, office, and hotel buildings were introduced, partially following the layouts of former industrial buildings [103]. However, these new structures surround the boiler house and turbine hall so closely that they significantly hinder the perception of the authentic power plant buildings [104].

Due to the poor technical condition of the buildings—resulting from the combustion of high-sulfur coal, which, after production ceased, formed sulfurous and sulphury acids that severely degraded the steel structures—a complete disassembly and regeneration of the structure was necessary [105]. This conservation effort enabled the preservation and reuse of the existing building frame (Figure 9c). The designers sought to retain the key industrial features of the architecture. In addition to preserving the main steel structure with brick infill, the gantry crane in the turbine hall was also retained. Unfortunately, most of the technical equipment had already been dismantled after the plant's closure. As a result, only artefactual remnants of the former machinery remain in the shopping center space. These include preserved control panels, switchboards, and meters, now serving as interior decor (Figure 9a). Ceramic insulators were notably reused to create interior design elements such as light fixtures, an information desk, and bench legs (Figure 9b) [106].

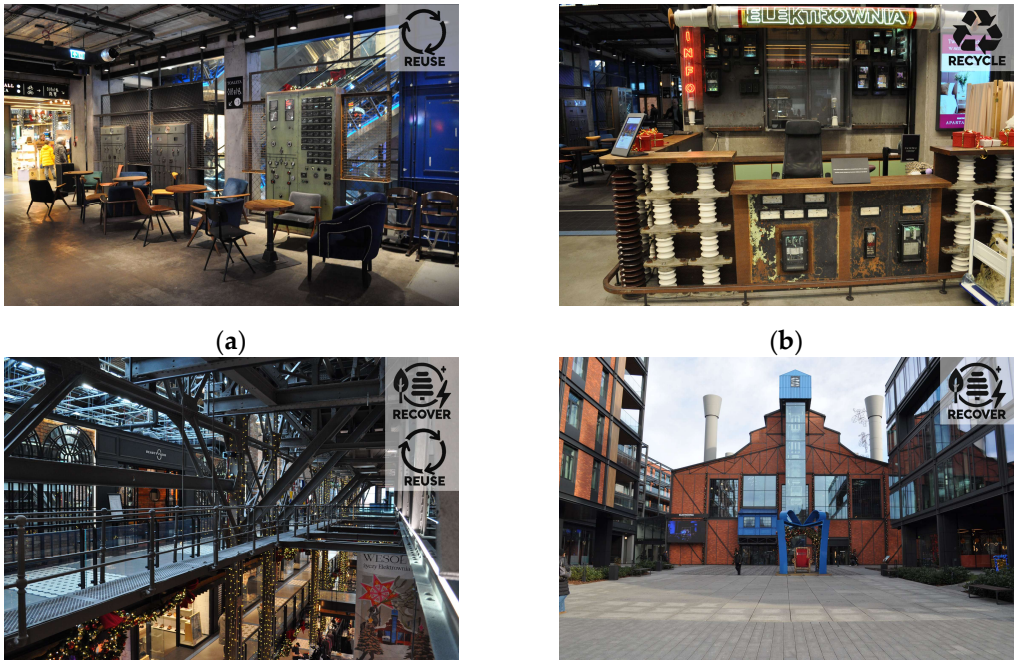


Figure 9. Example of applying 4R principles in the revitalization of the Powiśle Power Plant in Warsaw: (**a**) *reuse*—use of industrial equipment as decorative elements; (**b**) *recycle*—use of post-industrial components in interior design and small architectural features; (**c**) *recover/reuse*—reuse of the regenerated structural framework of the building; (**d**) *recover*—recovery of post-industrial space and buildings in the city center through redevelopment and the construction of new residential and commercial facilities. Source: author's photo (January 2025).

Regrettably, many of the new interior finishes merely mimic historical industrial forms. Numerous metal details in the shape of channels were used, and floor tiles replicate the pattern of original steel industrial flooring.

4.1.7. The Norblin Factory in Warsaw

The Norblin Factory in Warsaw is one of the most compelling examples of revitalization due to its location in the very center of Poland's capital and its proximity to the emerging high-rise office district. This location required a spatial approach that would maximize the use of the available site while preserving the identity of the place [107]. The project created a multifunctional space combining commercial, retail, gastronomic, and office functions with cultural and entertainment facilities [108]. A key aspect of the design was preserving the existing industrial buildings in their original condition as much as possible, along with securing numerous mobile pieces of industrial heritage. The economic compensation for the extensive and costly restoration work was the addition of new building volumes above the historic industrial fabric (Figure 10d) [107].

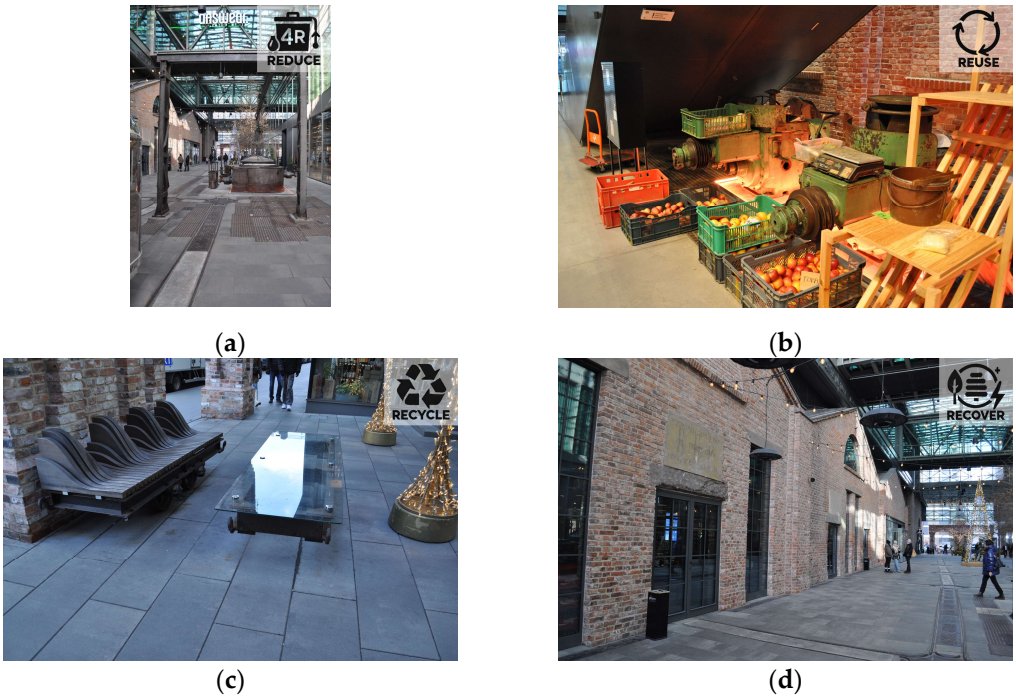


Figure 10. Example of applying 4R principles in the revitalization of the Norblin Factory in Warsaw: (**a**) *reduce*—reduction in waste generation through the use of existing floor finishes; (**b**) *reuse*—use of industrial equipment as preserved relics; (**c**) *recycle*—small architectural elements made from former building components and technical or transport equipment; (**d**) *recover*—recovery of post-industrial space and buildings in the city center through the extension of existing industrial halls. Source: author's photo (January 2025).

The revitalization of the site involved using the existing built fabric while striving to retain its appearance regardless of its condition. This decision was driven by a desire to authentically preserve the identity of the place—not only its former manufacturing function but also historical traces of World War II battles. The external plaster still bears bullet holes, and remnants of industrial trolley tracks have been preserved on site. Such an approach enabled waste reduction by retaining elements that, while no longer functionally needed, significantly contribute to preserving the post-industrial character of the site (Figure 10a).

The revitalization of the Norblin Factory also employed the "recycle" principle. Numerous post-production elements were repurposed into functional structures—primarily small-scale architectural features. The chassis of former transport trolleys were transformed into benches, tables, seats, and display cases (Figure 10c), while the historical crane structure was reused to create a canopy at the main entrance area. It is of great significance that

some of the machinery was left intact, so it was reused as preserved relicts of the factory (Figure 10b).

The revitalization process involved detailed inventory of the building and the number and condition of the industrial machines [107]. Many of these machines were entered into the register of movable industrial heritage monuments and now form part of the Norblin Factory Museum. Other items were reused as artifacts displayed in public spaces and interiors throughout the revitalized complex, primarily as decorative elements (Figure 10a).

Given the challenging conditions of the location, which necessitated investment and commercial profitability, the Norblin Factory serves as an inspiring example where the investor's pursuit of profit goes hand in hand with preserving the site's traditional values—also through the retention and reuse of post-production elements in line with the principles of the circular economy. It is also worth noting that the investor established a factory museum within the site, which presents not only the products of the former metallurgical plant but also documents and showcases historical production technologies.

4.1.8. "Koneser" Vodka Distillery in Warsaw

Due to its location in the heart of Warsaw's Praga district, the revitalization of the "Koneser" vodka factory is one of the most socially significant among the analyzed examples. It is considered a revitalization success, partly due to the substantial increase in land value in the surrounding area and has become a catalyst for neighborhood transformation. The post-revitalization functional program is highly diversified—new residential and office buildings were introduced, while the former industrial buildings were adapted for service-related functions, including offices, retail and gastronomy, as well as cultural functions such as small private art galleries and the Vodka Museum, which presents fragments of distillation equipment and historical productions technologies [109].

However, the principles of 4R were not applied in this project. Numerous buildings added in the second half of the 20th century as extensions to the original industrial complex were demolished. In their place, new buildings were erected, styled to resemble industrial architecture—featuring raw materials such as concrete, brick, and numerous metal details in the shape of channel sections. The public spaces include elements of small architecture in an industrial style, though these most likely do not originate from the original vodka factory and are instead newly added components. Consequently, this revitalization meets only the basic 4R criteria inherently associated with revitalization itself—recover of urban land and its value, and partial reuse of historical industrial structures (Figure 11).



(**a**) (**b**)

Figure 11. Revitalization of the Koneser Vodka Distillery—Praga Centre: (**a**) central square as an example of recover—transformation of a central urban space for commercial and cultural functions; (**b**) *recover* of buildings and inner-city space through the extension of historical structures. Source: author's photo (January 2025).

4.1.9. Warsaw Brewery

Located in the center of Warsaw's Wola district, the Warsaw Breweries represent an example of a commercial, mixed-use investment—primarily residential in character. The first attempts to revitalize the site took place at the beginning of the 21st century but were halted by the 2008 financial crisis [92]. As a result, a significant portion of the former buildings was demolished due to conflicts with the new development plans [66]; only the brewhouse, the Schiele House, and the laboratory were preserved [92]. Unfortunately, due to the few remnants of the original industrial structures, most of the revitalization involved the construction of new buildings that did not incorporate the former fabric. The only remaining features of the industrial heritage were the office building and the vaulted brewery cellar, which was attractively converted into a food court (Figure 12c).



(**a**) (**b**) (**c**)

Figure 12. Application of 4R principles in the revitalization of Warsaw Brewery: (**a**) *reuse*—former pipeline installations repurposed as small architectural elements demarcating space; (**b**) *recycle*—remnants of old columns transformed into lighting fixtures; (**c**) *recover*—recovering space and buildings for a food court. Source: author's photo (January 2025).

In the public space, former technological pipelines were recycled and repurposed to visually separate the historic brewery area from the adjacent urban street space (Figure 12a). Parts of cast iron columns were reused to create lamp posts (Figure 12b). The cellar's adaptive reuse, achieved with minimal structural interventions, along with the recycling of pipeline components and column fragments, represent the only traces of 4R strategies applied to industrial remnants. The new buildings refer to industrial forms merely through their architectural expression, such as the use of metallic louver systems on façades to echo the material palette of industrial architecture.

4.1.10. Żnin Sugar Factory

The Sugar Factory in Żnin serves as one of the best examples of how the principles of the circular economy can be applied in the revitalization of industrial sites. This project demonstrates the effective implementation of all four 4R strategies, showing the substantial impact that reusing existing elements can have on the perception of a former industrial facility transformed into a commercial complex—namely, a hotel and conference center with recreational functions.

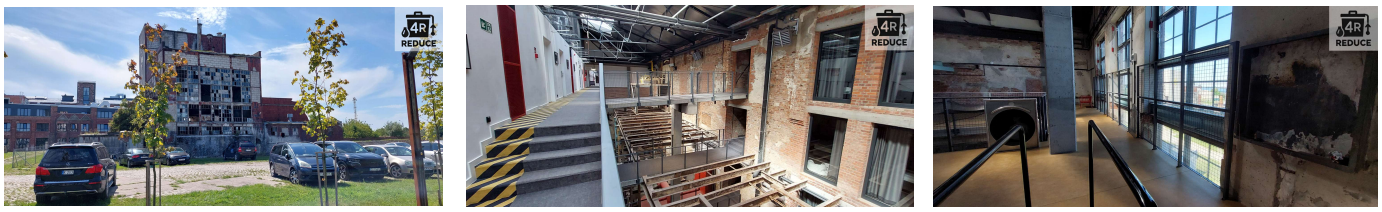
A crucial factor influencing the quality and character of the revitalization process was the preservation of the post-industrial buildings and infrastructure in relatively good condition since the cessation of production in 2005. One of the guiding principles during the design and execution stages was the retention of as much of the existing built fabric, machinery, and various factory artifacts as possible [110]. This approach enabled both an effective and visually striking recover of the former sugar production facility (Figure 13).



(**a**) (**b**) (**c**)

Figure 13. Revitalization of the Sugar Factory in Żnin: (**a**) main production hall after revitalization; (**b**) *recover*—repurposing of a former molasses tank; (**c**) *recover*—adaptation of smaller buildings, with a workshop shown in the photograph. Source: author's photo (August 2023).

The most significant 4R principle impacting the perception of the revitalized complex was the principle of *reduce*. None of the buildings were demolished, regardless of their construction period. Structures from the original 19th-century factory, as well as additions from the 1930s and 1970s, were all retained (Figure 14a) [111]. Within the existing fabric, demolition was reduced to an absolute minimum. New reinforced concrete hotel and conference structures were inserted into the open spaces of the former production and storage halls, without removing existing structural elements (Figure 14b). At the same time, the retained built fabric—including brick masonry walls, steel columns and beams, concrete floors, and technical installations—was preserved in its original, imperfect state, bearing traces of dirt and damage resulting from the site's former industrial use (Figure 14c).



(**a**) (**b**) (**c**)

Figure 14. *Reduce* in the revitalization of the Sugar Factory in Żnin: (**a**) retained structures not part of the original fabric of the factory; (**b**) entrance hall—reduction in demolition within the existing production hall structure; (**c**) preserved post-industrial traces—dirt, plaster chips, and imperfections in the joinery. Source: author's photo (August 2023).

The principle of reuse is also evident in numerous applications within the complex. Structural elements, rather than being dismantled, have retained their load-bearing function. Due to fire safety regulations, it was not possible to fully utilize the existing steel structure; however, it was repurposed as a permanent formwork for the new reinforced concrete framework (Figure 15a) [111]. In outdoor spaces, reuse is manifested through the adaptation of former site elements—narrow-gauge railway tracks have been incorporated into walkways and access roads, preserving the original width and alignment of the rails, while old industrial lighting poles have been adapted to support modern luminaires meeting contemporary requirements (Figure 15b). Reuse is also reflected in spatial and functional solutions: former conveyor belt links that once transported products between different parts of the factory now serve as internal corridors (Figure 15c), allowing hotel guests to move between program zones without the need to exit the buildings.

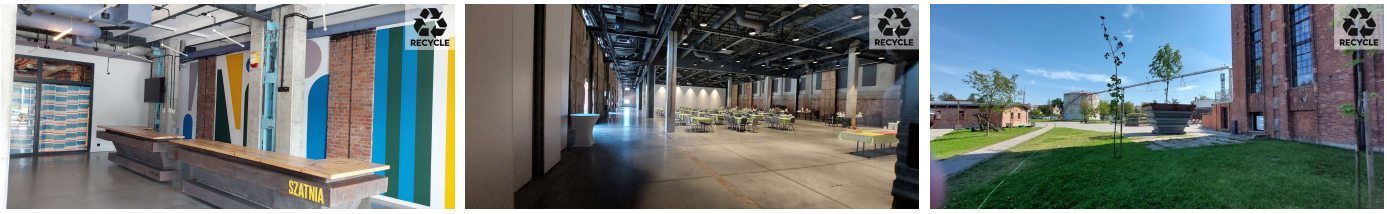
Moreover, during inventory and construction works, numerous post-production and construction-related items were discovered and collected for reuse within the complex. These included both small-scale service items, components of industrial machinery, sugar packaging, ceramic insulators, as well as larger elements such as wooden beams, roof structures, and boiler parts. The revitalized complex features numerous examples in which

these elements, after processing (recycling), were repurposed to serve functional roles. Nearly all counters—including reception desks, bars, and cloakroom stations—were made using recycled materials recovered from the site: the main hotel reception counter was built from repurposed steel pipes, while a section of a former boiler was used as the reception desk for the recreational zone (Figure 16a). Wooden beams were reused to form café bars, and ceramic insulators were incorporated into the counter of another food service point. One particularly compelling example of repurposing objects typically regarded as waste involves the construction of walls from jute bags previously used for transporting sugar (Figure 16b), as well as the use of old sugar packaging as wall finishes inside the lift [112].



(**a**) (**b**) (**c**)

Figure 15. *Reuse* in the revitalization of the Sugar Factory in Żnin: (**a**) use of the existing structure as permanent formwork; (**b**) reuse of existing lighting and installation poles to illuminate the area with new contemporary fixtures; (**c**) adaptation of the former conveyor bridge as a link between the hotel and the SPA area. Source: author's photo (August 2023).



(**a**) (**b**) (**c**)

Figure 16. *Recycle* in the revitalization of the Sugar Factory in Żnin: (**a**) repurposing of boiler fragments as reception desks in the recreational area; (**b**) reuse of jute sacks as acoustic insulation in the multifunctional hall within the conference area; (**c**) reuse of boilers as planters for tall greenery. Source: author's photo (August 2023).

Recycled elements were also extensively used in the open spaces between buildings. A particularly striking example, reinforcing the industrial character of the site, is the reuse of boilers or their parts as large tree planters (Figure 16c), or, when inverted, as pyramid-shaped planters for smaller vegetation. One boiler segment was also repurposed as a canopy above the entrance to the SPA area with a swimming pool.

As in other case studies, the Żnin Sugar Factory also features industrial machinery reused as relics—artifacts placed throughout the revitalized premises (Figure 17a). Unlike most other examples (with the exception of the Norblin Factory in Warsaw), these devices appear in significant numbers. In almost every zone of the complex, well-preserved industrial artifacts are visible (Figure 17b). Additionally, a dedicated exhibition space was created for office accessories formerly used by the factory's administration (Figure 17c).

A particularly noteworthy aspect of the revitalization project in Żnin is the deliberate preservation of all existing building elements along with their imperfections—damage, residue, and post-industrial "dirt." This approach not only significantly reduced the amount of waste that would have been generated through replacement or cleaning but also authentically reflects the industrial character of the former sugar factory. In addition, the intangible heritage of the former industrial site has also been preserved—one of the key

complementary elements of the hotel's operation is the organization of guided tours led by former factory employees, who share the history and everyday life of the factory.



(**a**) (**b**) (**c**)

Figure 17. Artifacts in the revitalized Sugar Factory in Żnin: (**a**) remnants of industrial equipment displayed in circulation areas; (**b**) preserved control cabin located in the main hall of the sugar factory; (**c**) collected factory instruments and office accessories exhibited on-site. Source: author's photo (August 2023).

4.2. Comparative Analysis Results

The revitalization of post-industrial sites inherently aligns with the principles of the 4R framework, particularly in terms of the recovery of land, spaces, and structures. It is important to note that the vast majority of contemporary revitalization projects in Poland concern industrial facilities now located within urban centers. Originally situated on city outskirts, these sites have been absorbed into the consolidated urban fabric. Consequently, all analyzed projects were assigned the *Recover* principle.

The presence of individual 4R principles across selected case studies is summarized in Table 2. Most of the revitalized sites do not meet all four criteria; only four out of ten projects demonstrated the implementation of the full 4R set. Three principles—*reduce*, *reuse* and *recover*—were identified in four other cases. The revitalization of the Goetz Brewery in Kraków applied only two principles: *reuse* and *recover*. One case study met solely the *recover* principle, referring to the reclamation and spatial revaluation of urban land.

Table 2. Application of 4R principles in the revitalization of post-industrial complexes.

Revitalized Post-Industrial Complex	Construction/ Production Shutdown/ Revitalization Completion	4R Principles			
		Reduce	*Reuse*	*Recycle*	*Recover*
Wrocław Brewery	1893/2004/2024	●●	●	●	●●
"Mamut" Bakery in Wrocław	1880/2006/2022	●●	●	—	●
Old Coal Mine in Wałbrzych	1770/1996/2014	●●	●●	—	●●
Goetz Brewery in Kraków	1840/2001/2016	—	●	—	●
Brewery in Ostrowiec Świętokrzyski	1908/1970/2019	●	●	—	●
Powiśle Power Plant in Warsaw	1904/2003/2021	●	●	●	●
Norblin Factory in Warsaw	1854/1981/2021	●	●●	●●	●●
"Koneser" Vodka Distillery in Warsaw	1897/2007/2018	—	—	—	●●
Warsaw Brewery	1846/2004/2021	—	●	●	●
Żnin Sugar Factory	1894/2004/2020	●●●	●●	●●●	●●

Legend: — not present; ● present; ●● commonly present; ●●● significantly present.

It is important to note that in some cases, such as the Warsaw Breweries, the poor condition and limited extent of the surviving building fabric made it impossible to apply all 4R principles.

The most frequently observed 4R principle across the analyzed sites is *reuse*. It typically manifests in the use of former industrial elements as small-scale architecture or architectural and urban details serving as visual references to the site's industrial past. This approach helps preserve the historical identity of the site. For example, in the case of the Koneser Vodka Distillery in Warsaw, various industrial-styled urban furnishings were observed, yet it was not possible to determine whether these were original elements from the factory or newly designed features referencing the site's heritage.

Similarly, at sites such as the Warsaw Brewery, the Goetz Brewery in Kraków, and the brewery in Ostrowiec Świętokrzyski, reused elements are largely decorative in nature and do not perform a structural or technical function.

The "Reduce" principle—minimization of waste and preservation of authentic structures and industrial remnants—was present in 8 out of 10 projects. In most cases, this was a direct result of heritage conservation regulations issued for the developments. This principle was particularly evident in projects located in smaller towns or those with a non-commercial profile—with the notable exception of the Norblin Factory in Warsaw. Among the analyzed cases, the revitalization of the Żnin Sugar Factory stands out as the project most comprehensively implementing all four 4R principles.

The least commonly observed principle was *recycle*, which involves processing existing materials to give them new functions within the revitalized structure or public space. Most commonly, this included reusing structural or installation components to create pergolas, trellises, or other architectural features that do not require high fire resistance or load-bearing capacity. A recurring strategy was also the transformation of post-production equipment into small architectural forms such as benches, planters, or seating elements.

A noticeable trend is that more recent revitalization projects—i.e., those completed in the second half of the studied decade—tend to incorporate sustainable development principles more extensively. This is particularly evident in the broader and more consistent implementation of 4R strategies.

5. Discussion

5.1. Opportunities, Challenges and Effects in Implementing 4R Strategies in Post-Industrial Revitalization

The application of the 4R principles (*reduce*, *reuse*, *recycle*, *recover*) in the revitalization of post-industrial buildings clearly demonstrates the potential to support the sustainable development of urban areas. However, the results of the comparative analysis indicate significant variation in the degree to which each principle has been implemented across the projects studied.

One of the key conditions for the effective implementation of the 4R strategy is the detailed inventory of the existing building fabric and technical infrastructure. Projects that employed modern documentation methods—such as 3D scanning or digital building models (e.g., Norblin Factory, Żnin Sugar Factory)—showed the greatest potential for material reuse and recovery. This confirms the thesis that actions aimed at preservation and reuse of structural elements should be planned at the pre-design stage.

Another important factor is the spatial and functional strategy adopted in each revitalization project. In cases where new functions were tailored to the existing spatial layouts (e.g., the Julia Coal Mine, Żnin Sugar Factory), the principles of "reduce" and "reuse" were more frequently and effectively realized. In contrast, commercial revitalization—

particularly in high-value urban locations (e.g., Koneser, Warsaw Breweries)—tended to apply circular economy strategies only partially or symbolically.

The least frequently implemented principle was *recycle*, which requires technological transformation of materials and additional energy input. Where applied, it mostly concerned the adaptation of former industrial elements into small architectural features such as benches or planters. In contrast, *reuse* was more common, though often limited to decorative rather than structural or functional uses.

The analysis also reveals a clear chronological trend: more recent projects (completed after 2020) more frequently incorporated sustainable design strategies, including circular economy principles. This may be attributed to growing environmental awareness, the influence of European regulatory frameworks, and wider availability of tools supporting sustainable architectural design.

5.2. Limitations in the Application of the 4R Principles

Despite the growing interest in the concept of the circular economy within the construction sector, the application of the 4R principles in the revitalization of post-industrial sites encounters a number of significant limitations.

First, the poor condition of post-industrial elements—including both materials and technical equipment—often prevents their reuse. In many cases, installations have deteriorated due to prolonged neglect or irreversible chemical processes (e.g., corrosion of steel components in coal-fired power plants).

Second, the overall technical state of buildings, especially those lacking ongoing maintenance, may necessitate partial demolition or substantial structural intervention. Such actions significantly reduce the potential for waste minimization or recycling of existing building fabric.

Third, the commercial value of a site's location directly affects the scale and pace of investment implementation. For properties situated in central urban areas, the pressure for rapid return on investment often excludes time-consuming and costly efforts related to material recovery or processing. In such contexts, investors tend to opt for new construction with industrial-style esthetics, rather than genuine implementation of 4R strategies.

All of the above factors suggest that while the 4R concept holds considerable potential in architectural practice, its effective application requires favorable technical, economic, and organizational conditions, as well as the conscious engagement of all stakeholders in the investment process—from designers and conservation officers to investors.

5.3. Future Directions

In light of the analyses conducted, it seems justified to recommend the following:

- Promoting modern inventory tools (e.g., 3D scanning, BIM), which facilitate the identification of elements suitable for reuse;
- Integrating the 4R principles into design guidelines already at the investment programming stage;
- Developing support systems (e.g., tax reliefs, grants) for investors implementing circular economy strategies;
- Creating databases of recovered materials and components potentially suitable for reuse in revitalization projects;
- Promoting best practices, such as the revitalization of the Żnin Sugar Factory, as exemplary cases of sustainable design with high adaptive and symbolic potential.

In the longer term, the implementation of the 4R principles in the revitalization process may become not only a tool for reducing the carbon footprint of the construction

sector but also a means of preserving cultural heritage in an economically and socially sustainable way.

5.4. Framework for Implementing 4R Principles in Post-Industrial Revitalisation

The proposed framework for implementing the 4R principles in architecture (Figure 18) is structured into four interrelated stages that reflect the complete life cycle of a revitalization project. The Strategic Level focuses on the preliminary assessment of a site and its built heritage, detailed 3D documentation, and the evaluation of feasibility and environmental impacts (including LCA and carbon footprint analysis). The Design Level involves the integration of the four principles—Reduce, Reuse, Recycle, and Recover—into architectural and engineering solutions, ensuring the optimal use of existing materials and structures while maintaining cultural and historical values. The Implementation Level covers design supervision during construction, coordination between the investor, design, and construction teams, as well as the documentation and traceability of reused and recycled materials. Finally, the Post-Occupancy Level introduces a feedback loop through environmental monitoring, verification of long-term durability and adaptability of the applied methods, and dissemination of knowledge to inform future projects. Together, these stages form a coherent methodological framework that links sustainable construction practices with the preservation of industrial heritage.

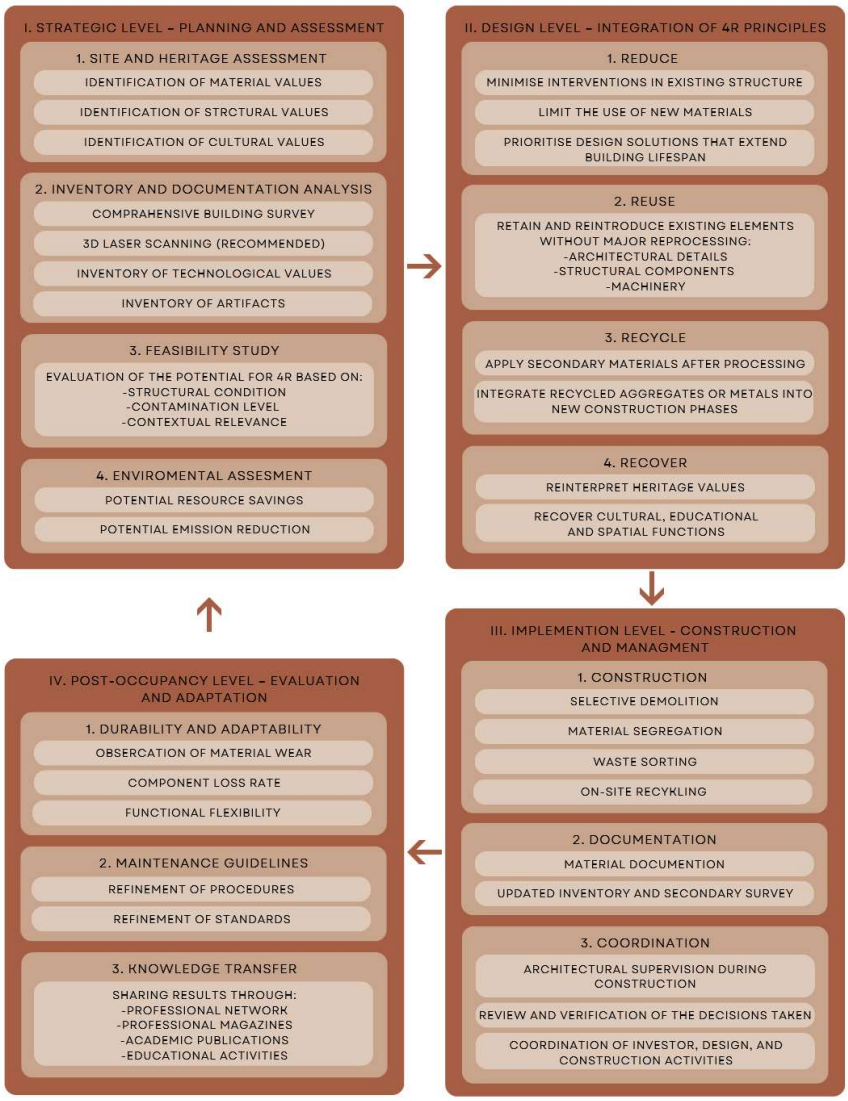


Figure 18. Framework of 4R Application in Building Redevelopment (authors, 2025).

6. Conclusions

The analysis of ten examples of post-industrial site revitalization in Poland has demonstrated that the principles of the circular economy—particularly the 4R model (*reduce*, *reuse*, *recycle*, *recover*)—can serve as a valuable tool supporting sustainable design processes. Although most of the examined projects implemented at least some elements of this approach, the full application of all four 4R principles proved to be rare.

The most commonly observed practice was the reuse of selected building elements, often for decorative or symbolic purposes. The principle of waste reduction (reduce) was also present, especially in cases where demolition and interventions in the existing fabric were minimized. Material recycling (*recycle*) was used far less frequently, primarily due to the high costs and technological complexity involved. Spatial recovery (*recover*) can be considered fulfilled in all cases, as it is a natural component of revitalization understood as the restoration of value to urban space.

The identified limitations—particularly the poor technical condition of buildings, the lack of preserved industrial equipment, and economic pressure in high-value locations—indicate that the effective implementation of the 4R principles requires not only favorable technical conditions, but also the conscious and long-term commitment of investors and designers.

Nevertheless, revitalization projects such as the Żnin Sugar Factory or the Norblin Factory demonstrate that it is possible to reconcile economic goals with environmental responsibility and the preservation of industrial heritage. Therefore, further promotion of circular economy-based solutions seems justified, as well as continued research into their actual environmental, economic, and social effectiveness.

It should be noted that the research presented in this paper did not include an analysis of the impact of the completed revitalization projects on their surroundings, including economic and social factors. The assessment of revitalization phenomena in these contexts requires further research, which may serve as a foundation for future scientific studies. Another aspect worthy of continued investigation is the evaluation of Life Cycle Assessment (LCA) data and the carbon footprint of the undertaken actions, as well as their actual environmental effectiveness. A valuable research direction would be to conduct, within approximately five years, a comparative analysis verifying the long-term durability of the applied 4R methods, which is currently not possible due to the relatively short time since the projects were completed.

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Abbreviations

The following abbreviations are used in this manuscript:

CE	Circular Economy
4R	4R principle—reduce, reuse, recycle, recover
CDW	Construction and Demolish Wast
UN	The United Nations
UE	The European Union

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