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The SPPD-WRF Framework: A Novel and Holistic Methodology for Strategical Planning and Process Design of Water Resource Factories

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Abstract: This paper guides decision making in more sustainable urban water management practices that feed into a circular economy by presenting a novel framework for conceptually designing and strategically planning wastewater treatment processes from a resource recovery perspective. Municipal wastewater cannot any longer be perceived as waste stream because a great variety of technologies are available to recover water, energy, fertilizer, and other valuable products from it. Despite the vast technological recovery possibilities, only a few processes have yet been implemented that deserve the name water resource factory instead of wastewater treatment plant. This transition relies on process designs that are not only technically feasible but also overcome various non-technical bottlenecks. A multidimensional and multidisciplinary approach is needed to design water resource factories (WRFs) in the future that are technically feasible, cost effective, show low environmental impacts, and successfully market recovered resources. To achieve that, the wastewater treatment plant (WWTP) design space needs to be opened up for a variety of expertise that complements the traditional wastewater engineering domain. Implementable WRF processes can only be designed if the current design perspective, which is dominated by the fulfilment of legal effluent qualities and process costs, is extended to include resource recovery as an assessable design objective from an early stage on. Therefore, the framework combines insights and methodologies from different fields and disciplines beyond WWTP design like, e.g., circular economy, industrial process engineering, project management, value chain development, and environmental impact assessment. It supports the transfer of the end-of-waste concept into the wastewater sector as it structures possible resource recovery activities according to clear criteria. This makes recovered resources more likely to fulfil the conditions of the end-of-waste concept and allows the change in their definition from wastes to full-fledged products.

Keywords: sustainability assessment; sustainable urban development; urban water management; wastewater treatment; conceptual process design; cost-benefit analysis; resource recovery; circular economy; water resource factories; multiple-criteria decision making

1. Introduction

Implementing resource recovery from waste streams is a complex task and requires multidimensional planning and a whole-system perspective [1]. Domestic wastewater cannot any longer be considered as "waste" because it is a resource full of clean water, energy, and valuable materials including nutrients [2]; a sustainable municipal wastewater treatment plant (WWTP) recovers various resources from the wastewater stream and feeds into the circular economy [3–5]. To emphasize the need for a paradigm shift towards resource recovery as a standard procedure in the wastewater sector, the term WWTP has been changed into WRF (water resource factory) [6]. When existing WWTPs approach the end of their expected service life span, a unique window of opportunity exists to replace the aging infrastructure with innovative WRFs that integrate resource recovery technologies. Beyond the treatment of wastewater for safe discharge into the environment, a WRF may reduce stress on water resources through water reuse, provide renewable energy, recover various products including fertilizers and contribute to economic activity [7]. Reaching the transition from WWTPs to WRFs can mean a complete reimaging of the treatment process or modifying an existing process design by integrating innovative recovery technologies [8].

Generally speaking, decision making in the early design stage of wastewater treatment processes is often based on the previous experiences of the involved process engineers [9]. Usually, the overall objective of WWTP process design is to find the process among numerous alternatives that optimally treats a given influent under the prerequisite of process costs on the one hand and robust treatment performance driven by legal effluent quality requirements on the other [10,11]. Due to increasing available treatment technologies, WWTP design has become more and more complex in recent years. The resulting multi-criteria process design problem for an optimal treatment process has successfully been tackled by mathematical problem optimisation in superstructure methods using stoichiometric coefficients and kinetic constants [12–14], or by applying computational environmental decision support systems in the process design procedure [15]. Software to choose between alternative treatment process designs on the basis of their techno-economic performance has been developed including also environmental impact assessment criteria [16]. Despite these outstanding WWTP design methodologies, little attention has yet been given to design a WWTP from a resource recovery perspective instead [11,17]. Although considerable interest in the technical development and integration of resource recovery technologies into WWTPs exists, resource recovery is not yet a major objective in WWTP design methodologies. The rationale and necessity to perceive wastewater as a resource has been emphasized intensively in the water sector but there are only few examples of actual WWTPs where an integrated design approach has been taken and multiple resources are recovered by a newly implemented process [18]. The rather narrow decision-making perspective limited to cost effectiveness and robust treatment performance excludes resource recovery as a crucial factor for a more sustainable urban water cycle because it blocks the transition from WWTPs towards WRFs [19].

The rapidly growing number of recovery technologies increases the complexity of process design choices further [20]. Consequently, designing WRFs in the future requires us to make resource recovery a measurable process design objective. However, the technical feasibility of certain resource recovery technologies alone does not guarantee their successful integration into innovative process designs, because several existing non-technical bottlenecks need to be tackled as well to successfully implement available recovery technologies. Those bottlenecks relate to economics and value creation for recovered resources, and also to potential emissions and health risks and to policies and people's perceptions. If these bottlenecks remain unsolved, they impose severe uncertainties that may hinder decision makers in water utilities to implement WRFs in the future [5]. The design of WRFs requires therefore strategical planning from a multi-dimensional perspective and can only be successful if the design space and decision-making process is opened up towards a multidisciplinary team effort. Expertise from multiple technical and non-technical domains need to complement the traditional process engineering tasks focused on treatment performance and process cost.

The goal of the framework proposed in this paper is therefore to establish resource recovery as a major objective in the design of new wastewater treatment processes that can justifiably be labeled as WRFs instead of merely WWTPs. It aims to move forward from the concept that wastewater is a resource and answer the question: how to design or retrofit treatment processes from a circular economy perspective that cope with multidimensional site-specific circumstances and are therefore ready for implementation? This requires a novel and holistic framework that we named "the SPPD-WRF framework" because it combines strategical planning (SP) and early stage process design (PD) of innovative water resource factories (WRFs). Processes planned and designed along this novel framework cope with:

- legal effluent standards,
- marketability and value creation for recovered resources,
- technical process feasibility,
- economic feasibility,
- environmental impacts,
- and the inclusion of stakeholders into decision-making procedures.

To fulfill these multidisciplinary necessities, the SPPD-WRF framework follows the project management principle "begin with the end in mind" [21] and transfers it to WRF process design. It structures not only the process-related design space of WRFs, but also the market-related design space by introducing a production system perspective into the early design stage. WRFs ideally recover marketable commodities [5,22,23], and hence marketability related criteria like, e.g., the demands or monetary values of recovered resources need to be assessed early. The underlying rationale to assess the marketability of recovered resources is the following: the concept of a circular economy emerged from the observation of natural matter cycles that do not know wastes but only resources and aims to transfer those natural principles into societal production–consumption patterns. However, the current market economy aims for the perpetual short-term economic value increment of individuals, organisations and states. Consequently, combining circular resource solutions with the current economic model requires that economic value is created from the cycle in a reasonable timeframe.

Resource recovery technology integration alters the overall technical, economic, and environmental performance of municipal WWTPs. The proposed framework responds to these alterations by extending existing WWTP design and assessment methods and suggests a novel method suitable for WRFs. New technical challenges like, e.g., the integration of downstream processes and refinement steps of recoverable biomaterials are considered by including specific engineering expertise during process configuration and introducing criteria to assess the resource recovery potential of a process. Compared to WWTPs, the economic performance of a WRF is no longer only determined by investment and operational costs but also by revenues from recovered resource sales, while environmental impacts are determined not only by emissions but also by abated emissions that stem from avoided conventional resource extraction and consumption. The SPPD-WRF framework considers these new requirements and allows a complete assessment of technically feasible WRF processes in those non-technical dimensions. Since early stage process assessment relies greatly on secondary data, meaning any data that are examined to answer a research question other than the question(s) for which the data were initially collected, it is important to analyze the certainty of the applied assessment criteria [24].

The SPPD-WRF framework contributes also to the end-of-waste concept that has been manifested in the Waste Framework Directive 2000/98 to facilitate recycling by defining that waste is no longer perceived as such when it has undergone a recovery process in accordance with the following four conditions: (i) the substance or object is commonly used for a specific purpose; (ii) a market or demand exists for such a substance or object; (iii) the substance or object fulfils the technical requirements for its specific purpose and meets the existing legislation and standards applicable to products; and (iiii) the use of the substance or object will not lead to overall adverse environmental or human health impacts. Waste streams that are candidates for this change of definition must have undergone a recovery operation that complies with specific criteria which are yet to be defined for municipal wastewater [25]. By introducing a holistic set of WRF assessment criteria, the SPPD-WRF framework aims to facilitate the introduction of the end-of-waste concept into the municipal wastewater context.

2. Materials and Methods

The SPPD-WRF framework for strategical planning and early-stage conceptual process design of WRFs has been developed by reflecting on the multidimensional and multidisciplinary requirements for implementing WRFs successfully. It uniquely combines existing methodologies from different research fields: wastewater treatment and wastewater process design, industrial process engineering, project management, circular economy, market analysis, techno-economic assessment, and environmental impact assessment. Firstly, an extensive literature analysis of these research fields was carried out. Secondly, procedures that are useful for designing WRFs from a holistic viewpoint have been identified in the literature. Thirdly, a stepwise structure has been defined that allows the strategical planning and process design of WRFs from a holistic perspective. Fourthly, quantitative and semi-quantitative assessment criteria to make innovative WRF process designs comparable to each other in different performance dimensions were adapted from sources in literature.

The project management concept of a development funnel and stage gating [26], which reduces the number of initially configured process designs gradually during successively executed assessments (Figure 1), was used as a theoretic model for the assessment of WRF process designs. The original model was adjusted for those assessment dimensions useful to estimate the performance of WRFs. Each assessment represents a gate decision point, and only when a process is assessed with promising results may it pass to the next assessment. When the results are unsatisfactory in a particular assessment, a re-design can be carried out to improve the process performance and feed it to the next assessment. If a process assessment result indicates that a process is unfeasible, it can be discarded. A process is first assessed for its marketability of recoverable resources, because techno-economic and environmental impact assessments are in general more time consuming and thus more costly. Consequently, only those process designs that are promising in terms of value creation are suggested to be further assessed. After the marketability, technical feasibility, economic performance, and environmental impacts of innovative WRF processes have been assessed, an uncertainty analysis of the applied assessment criteria is proposed. In addition, the framework includes stakeholder inputs in the formulation of process design objectives and during the final process selection step whereas the other steps, including technical process configuration and process assessments, are supposed to be carried out by specialists of different expertise.

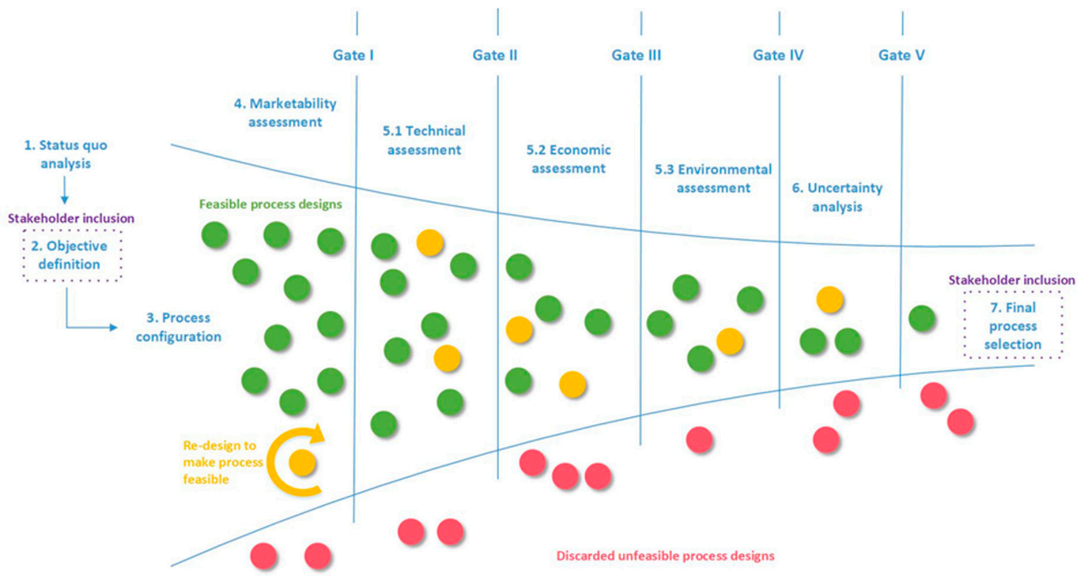

Figure 1. Funnel development and stage gating model adapted from [26] to make it specially applicable for water resource factory (WRF) process design purposes.

3. Results and Discussion

The SPPD-WRF framework is a prescriptive methodology that incorporates seven consecutive steps including four WRF process assessment dimensions. In addition to the process-related technical, economic, and environmental dimensions, the value creation and marketability of recovered resources were also considered:

Step 1: status quo analysis;
Step 2: design objectives definition with stakeholders;
Step 3: process configuration and analysis by mass balances;
Step 4: marketability assessment;
Step 5: technical, economic and environmental assessment;
Step 6: uncertainty analysis;
Step 7: final process selection with stakeholders.

A detailed overview of the framework is shown in Figure 2. It structures the decision-making process during the early stage planning and process design phase in a way that the finally selected process meets objectives carefully pre-defined by stakeholders; recovers marketable resources; and is technically feasible, cost effective, and environmentally friendly. The framework provides a holistic but flexible instruction manual in the sense that the proposed assessment criteria can be selected according to their usefulness for a specific WRF design project at stake, while others can be added if necessary.

3.1. Step 1: Status Quo Analysis

3.1.1. The Existing Treatment Process

First, the current treatment performance can be measured by influent and effluent characteristics in consideration of legal effluent standards. Treatment performance measurement methods have already been developed for WWTPs and can be used at this step [16,27,28]. Ref [27] recommends the measurement of 17 key performance indicators (KPIs), including ones that measure influent characteristics, treatment efficiency, and effluent quality. Most key variables do not need to be measured in every treatment unit but can be calculated from influent and effluent concentrations using existing stoichiometric models or simpler mass balance methods [9,29,30]. In addition to existing legal effluent discharge requirements, potential new legislation can be considered in this step. Emerging pollutant removal is a growing concern of legislators and stricter regulations which include new contaminant categories are expected in the future [31]. Additionally, stricter effluent nutrient concentrations are being debated which would require process designers to change treatment strategies and add further treatment steps to a process or re-design to meet the legal limits [32].

The operational costs of the existing process can either be estimated based on pollutants removed, e.g., € per kg phosphorus, or on the volume of wastewater treated (€ per m^3). Both measures may vary over time and therefore have advantages and disadvantages [27]. In the literature, the cost estimations of WWTP operations usually consider five main operational cost factors: energy consumption, maintenance, waste disposal, labor, and reagents [33,34]. Furthermore, if the existing plant already recovers resources, this can be assessed by determining the percentage of recovered energy and materials compared to influent concentrations [27]. Table 1 provides a set of criteria that we suggest be applied to analyze the status quo of an existing WWTP.

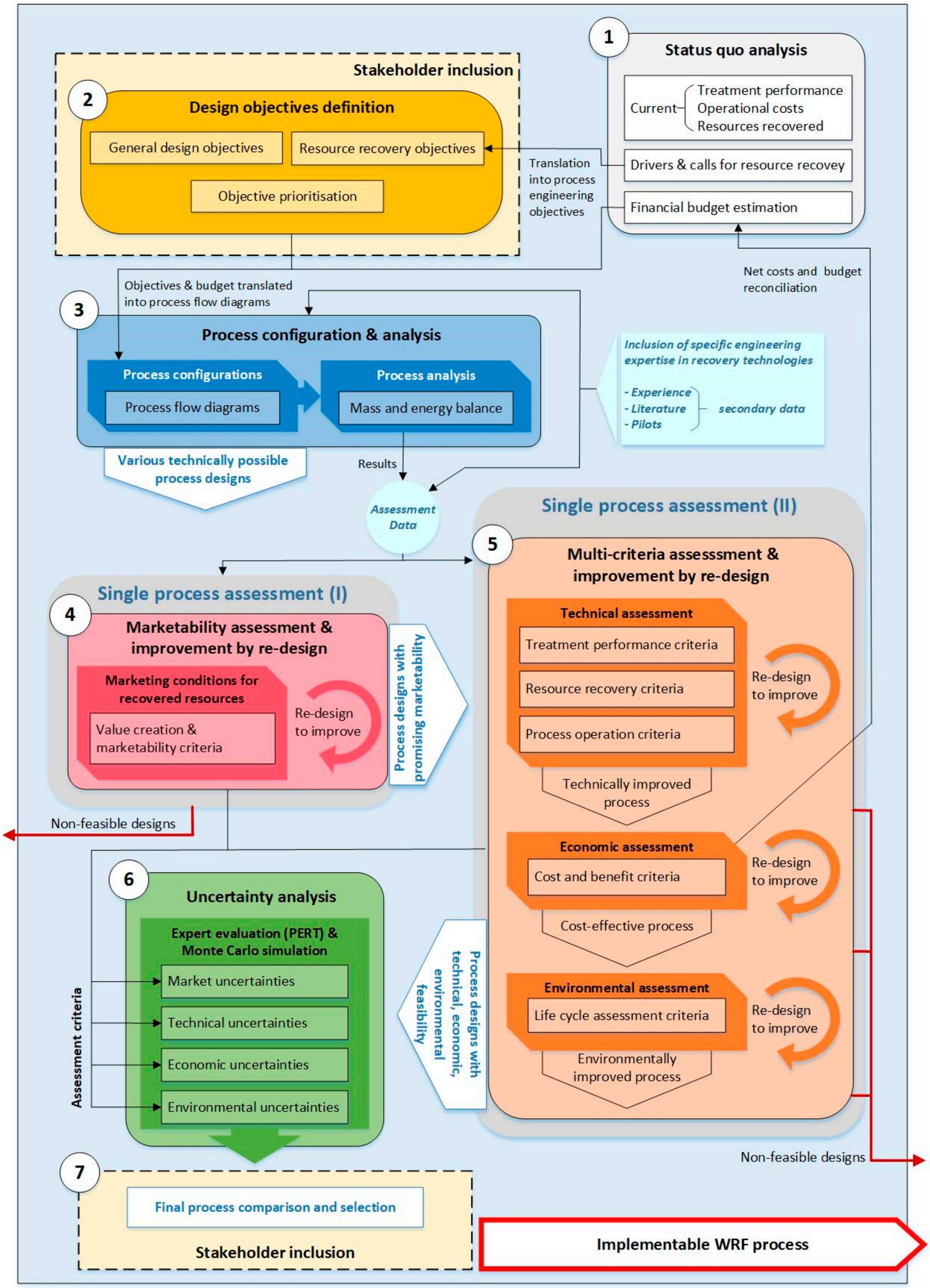

Figure 2. The SPPD-WRF framework for strategical planning (SP) and early stage conceptual process design (PD) of water resource factories (WRFs).

Table 1. Criteria to assess the current treatment performance, operational costs, and resources recovered by the current wastewater treatment plant WWTP based on the influent flow rate.

Treatment Performance	Explaining Remarks	Reference
Flow rate	Average influent load per day	[35]
Effluent quality	COD removal efficiency	[35]
	BOD_5 removal efficiency	[35]
	Total Kjeldahl nitrogen (TKN) removal efficiency	[35]
	TP removal efficiency	[35]
Operational Cost	**Explaining Remarks**	**Reference**
Labor	Work hours and wages (e.g., operation, training)	[36]
Energy	(Net) energy cost for consumed kWh	[16]
Maintenance	Maintenance time and maintenance cost (e.g., repairs, inspection, replacements)	[36]
Waste management	Quantities, fees charged for disposal, transport costs (e.g., sludge)	[16]
Reagents	Costs of required chemicals (e.g., methanol, iron chloride, polyelectrolyte)	[16]
Resource Recovery	**Explaining Remarks**	**Reference**
Resource quantities	Quantification of already recovered water, energy, fertilizer, other products	[22]

3.1.2. Budget Determination

Since financing poses a perpetual challenge for the research, development, demonstration, and deployment of WRFs [7], it is necessary to determine the budget for a new process and its depreciation rate at an early stage, as both are important boundary conditions to be considered throughout the conceptual process design phase. All funds that are likely to become authorized to plan and construct the plant, as well as the budget for operating the plant, should be estimated here. This requires the analysis of funding opportunities like, for example, European Union (EU) grants or public–private partnerships (PPPs) using different forms of lease contracts [37]. In particular, the investment costs allowed for the new WRF will be an important guideline in step three, where process engineers configure possible process designs. Later in step five, the process costs of WRF process designs will be estimated by a cost benefit analysis (CBA), and the results need to be reconciled with the sum of authorized funds to identify any variance in the funding limit.

3.1.3. Drivers and Calls for Resource Recovery

The concept of the circular economy is increasingly seen as a complete or partial solution to sustainable development and the fulfilment of the United Nations sustainable development goals (SDGs) [38,39]. Since WRFs relate to several SDGs (Table 2) which are also incorporated into European and national political objectives, it is useful to know how a WRF contributes to their fulfilment to trigger political support for the plans. In addition to sustainability as a driver, there might be actual calls for action for more circularity in the urban water cycle within the municipality or region where the WRF is planned. For example, calls for action for water reclamation and reuse could be seawater intrusion into groundwater [40], ecosystem service loss in dried out river banks [41], or temporary water shortages in local agricultural systems [42]. If stricter legal effluent qualities are expectable in future wastewater regulations, this can be a call for implementing advanced treatment units that would also facilitate water reclamation if a process is accordingly designed [43]. The need for advanced treatment would imply higher energy requirements of the WWTP and, therefore, integrating energy recovery technology into process designs to keep energy costs low could be a follow-up call for action [3]. Another call for energy recovery could be that a governmental body puts pressure on the water utility at site to decrease the greenhouse gas emissions of the urban water cycle and increase renewable energy consumption to contribute to political carbon emission goals, which has been the case in the Netherlands [44]. This would raise the call for, e.g., the recovery of chemical but probably even more the recovery of thermal energy stored in the wastewater stream [45,46]. Furthermore, policies that make it mandatory to recover phosphorous (P) from sewage sludge, as required by German legislation valid from the year 2023, resemble a similar pressure that leads a call for action on P recovery technology integration into the WRF process [47]. Given these reasons, this step aims to analyze all existing or expected drivers and calls for resource recovery.

Table 2. Sustainable development goals [38] that a WRF may directly or indirectly contribute to.

SDG Number	SDG
6	Clean water and sanitation
7	Affordable and clean energy
9	Industry, innovation, and infrastructure
11	Sustainable cities and communities
12	Responsible consumption and production
13	Climate action

3.2. Step 2: Objective Definition

3.2.1. Considerations of Stakeholder Involvement

After the status quo has been analyzed, it is necessary to identify the stakeholders of the new WRF and include them into the formulation of design objectives. In general, a broad range of stakeholders should be included in the process planning, especially experts like, for example, water utility managers, operators, WWTP process engineers, regulators, and elected officials. However, also non-experts—such as local neighboring communities and public interest groups, as well as other parties affected by the new WRF—need to be included in the process of stakeholder engagement. The importance of appropriately timed stakeholder participation in the decision-making process has been acknowledged as a key component of socio-technological planning and design methodologies in water management projects, because stakeholder participation is a vital component of embedding sustainable solutions and trust building [19]. The key benefit of involving stakeholders already in the definition of objectives is that it may increase support and minimize the resistance of critical stakeholders towards the process implementation [48]. Stakeholder participation facilitates positive social learning, minimizes and resolves conflicts, elicits and uses local knowledge, and achieves the greater acceptance of water management decisions [19]. Nevertheless, as stakeholders can have different preferences regarding the new process, decision making can become more complex with an increasing number of stakeholders [49].

Therefore, it is debatable at which planning stage all stakeholders are included into the design process and may depend on project-specific circumstances. It is very likely that the early stage process design team consists of a variety of experts that are aware of the potential differing interests of non-expert stakeholders and hence are able to define general process objectives from a well-informed viewpoint. Therefore, it might be feasible to follow the approach from [50], who consider full stakeholder inclusion after the general design objectives have been defined by a team of experts. Afterwards, other stakeholders need to be informed and included to have the opportunity to discuss the defined objectives and possibly add others. In any case, the inclusion of non-expert stakeholders, like the public, improves social sustainability factors like equity [51] or community involvement [36] and reveals which interest groups are made worse off or benefit more than others from the planned WRF. As different stakeholder analysis and participation methods exist, all showing unique weaknesses and strengths, we refer to the review of [52] to develop an approach most suitable for a specific planning case. However, we suggest that the following design objective definition include all relevant expert and non-expert stakeholders and its results resemble commonly agreed goals.

3.2.2. Design Objectives Definition

As explained in the introduction, objectives in conceptual WWTP design are primarily based on investment and operational costs and treatment performance according to legal effluent discharge limits [53]. In addition, environmental impacts beyond the discharge of effluents into surface water bodies have been considered as important criteria in some WWTP design literature [54,55]. As the fulfilment of these three objectives also remains crucial in WRF design, resource recovery needs to be understood as an equally important but additional design objective that can only be fulfilled if innovative processes meet the three initial objectives. Therefore, the SPPD-WRF framework proposes that the design space of WRFs be structured by these interlinked four key objectives:

- Legal effluent quality,
- Economic feasibility,
- Environmental friendliness,
- Resource recovery potential.

The drivers and calls for resource recovery analyzed in step 1 represent process requirements that need to be translated here into recovery objectives that will guide the process configuration carried out in step 3. For example, if a political will has been identified to decrease the municipal greenhouse gas emissions (GHG), decreasing the fossil energy consumption of the current WWTPs by a defined percentage has to be formulated here as an objective for the new WRF. If a certain water reuse type has been identified as useful to solve a water supply issue within the regional water cycle, the requirements for the quality and quantity of reclaimed water should be formulated as a clear objective here. Furthermore, the status quo analysis possibly revealed some weaknesses of the current WWTP which should be improved in the future by the new process and can be formulated as design objectives here. An example may be high operational cost factors due to a high usage of reagents or large waste sludge volumes leading to high disposal costs. How the new WRF should perform in those identified criteria can be quantified here. Another objective defined here could be to design a process that fulfils a better removal of emerging pollutants if this was identified by stakeholders as a growing concern.

After the objective definition, a preliminary prioritization of objectives can be found together with all stakeholders. Several methods may be applicable to find a hierarchy for the formulated objectives. To determine which resources should be prioritized over others if recovery measures compete with each other can be solved by a value pyramid that allows the ranking of recovered resources according to their economic value and estimated volume [22]. Operational cost reduction is likely to be a major objective in most process design projects and promotes the prioritization of recoverable products of higher value over those of lower value. Therefore, the integration of recovery technologies that recover chemical oxygen demand (COD) as valuable biochemicals with high yields instead of low-value methane might be formulated as a general objective [56]. Another tool to find the prioritization of defined design objectives is the analytical hierarchy process (AHP), which reduces rather simple decision problems into pairwise comparisons assessed by weighted evaluation criteria [57]. The decision-making team, together with key stakeholders, assigns each objective a weight factor which reflects a particular objective's relative importance against the other objectives in percentage so that the sum of all weights adds up to 100% [51]. However, ranking objectives may also be achieved by discussion in stakeholder meetings, and many objectives may be prioritized over others simply because they are a prerequisite for the new process implementation, like, for example, being cost effective and fulfilling legal effluent standards. Regarding the desirability of recovering a certain resource, it should be argued that water recovery is preferable over energy recovery because it is more critical, as energy can be obtained from a great variety of alternative sources including renewables [58]. Thermal energy recovery from effluents has recently been formulated as a priority over chemical energy recovery, as it has a higher potential to design carbon neutral processes. Instead of energy, organic carbon should be recovered as a biomaterial because then its energy content is preserved to a higher extent [46]. For nutrient recovery, phosphorous recovery has been referred to as preferable over nitrogen recovery due to its projected scarcity [59]. The further prioritization of resources to be recovered will become clearer during individual process assessments in steps 4 and 5, where some resource recovery pathways will be discarded due to marketability constraints and techno-economic or environmental unfeasibility.

3.3. Step 3: Process Configuration and Analysis

3.3.1. Process Flow Diagrams

Wastewater treatment process configuration is the selection of technologies from numerous alternatives to interconnect them to possible process flow diagrams (PFDs) [13]. The primary goal of this step is to configure a variety of process designs that use innovative technologies to recover all the resources that have been defined as recovery objectives in the previous step. Other already defined objectives related to effluent quality, technical-economic feasibility, and environmental friendliness are of secondary concern in this step. They will be thoroughly assessed in step 5, where each PFD can still be re-configured to match them. For now, process designers can creatively design innovative processes from a resource recovery perspective and simultaneously keep the boundary conditions like effluent quality and investment cost budget in mind but not focus on them. Regarding the latter, the process design team can integrate unit operations already existing in the status quo process (analyzed in step 1) in their new process configuration if convenient. Keeping existing and potentially useful unit operations may reduce investment costs, which will be assessed later in step 5.

As in other process engineering fields, the selection of technologies in wastewater treatment process configuration is often based on heuristics and the experience of responsible process engineers [60,61]. However, the configuration of PFDs from a resource recovery perspective must be a creative and innovative procedure that overcomes the habitual attempt to integrate dominant technologies that are already well known by involved process engineers. There is a clear necessity to bring a broad range of experts from different technical disciplines together, as not only treatment but also recovery technologies are integrated into PFDs. The latter requires knowledge beyond the wastewater process engineering domain like, for example, the production and downstream processing of biopolymers [61] or the recovery process of protein from ammonia dissolved in side streams [62]. If water reclamation has been defined as an objective, know-how that is probably more commonly applied in the technical domain of potable water supply is required and should be represented in the process configuration team [63].

To reach a creative design procedure, state of the art applicable technologies should be reviewed using recent literature [5,8,64]. This way, missing expertise for certain processes intended to be integrated can be invited to join the configuration step. In addition, an outlook on the future potential of technologies that are not fully mature yet is recommended. Assessing innovative technologies according to when they can be operational in full scale is an important criteria for designing innovative WRFs [22]. Data and information to estimate the potential for up-scaling innovative technologies that are still at pilot scale can be collected from the literature, communication with experts and researchers, and from pilot plants [64]. The maturity of innovative technologies may be then systematically assessed using the technology readiness level method (TRL), which ranges from 1 (basic principles observed) to 9 (technology proven in operational environment) [65]. Some of the objectives defined in step 2 might be interrelated because they can be achieved by integrating the same technology. Those potential key technologies that are able to tackle several objectives should be identified and integrated into one or several PFDs. For example, if the objectives of waste sludge reduction and energy neutrality have both been formulated, primary sludge up-concentration with chemically enhanced primary treatment (CEPT) and subsequent anaerobic sludge digestion should be integrated into a PFD, as this combination of technologies may tackle both objectives [66].

3.3.2. Mass and Energy Balances

After a variety of PFDs have been configured to likely meet the defined recovery objectives, a better understanding of the processes and implications of specific technology integration is needed. This can be achieved by the method of mass and energy balances (MEBs), which are an excellent method to analyze how selected wastewater constituents convert in a process [67]. Selected wastewater constituents can be tracked throughout the PFD to quantify concentrations in targeted flows, like, for example, in waste sludge and effluent. Finally, the results will reveal products, wastes, and emissions associated with the process in space and time. Modelling the mass and energy conversions in each process unit provides insight into how integrated treatment and recovery technologies may influence each other and treatment performance. Thus, the understanding of how and where innovative resource recovery units preferably become integrated is enhanced [64]. [9,28,29] provide data and detailed procedures for the selection and identification of key variables of WWTPs to perform accurate balances of COD fractions, total suspended solids (TSS), total Kjeldahl nitrogen (TKN), and total phosphorous (TP). The functional unit of the MEBs should be the influent flow rate to make the MEBs of different PFDs comparable to each other [33].

An integrated mass and energy balancing approach needs to include all unit operations that are planned for the on-site resource extraction, processing, and refinement of products [67].

More specific data, like, e.g., the operating parameters of innovative technologies, can be collected from scientific literature, existing pilot- or full-scale applications, or experience [61]. The balancing can be conducted by applying specialized process-modelling software like, e.g., Aspen Plus, but also more generic calculation tools can be used. Another reason why the analysis of configured processes with MEBs is a crucial step in WRF design is that results will reveal for each PFD the recoverable resource quantities, and therefore possible trade-offs between integrated recovery technologies in different PFDs are revealed. Influent constituents like COD or P can be recovered as different products depending on the recovery technology applied in a process [22]. The integration of a particular recovery technology restricts others, and therefore which PFDs convert constituents into which and how much products should be analyzed. An example of these possible trade-offs between process configurations is cellulose recovery by influent sieving, which could reduce the methane recovery rate in anaerobic digestion [22] compared to a process that recovers no cellulose from the influent. Whereas, methane recovery in turn could reduce the recovery potential of biomaterials like, e.g., polyhydroxyalkanoate (PHA) [56]. In addition to trade-offs, interrelations and synergies between particular resource recovery technologies will become more obvious by conducting MEBs. One possible interrelation relates to the water-energy nexus. Water reclamation by advanced treatment processes, like, e.g., the membrane-based treatment of secondary effluents, may require 0.7–1.5 kWh m^{-3} additional energy input [68]. Therefore, if water reclamation has been formulated as a priority, it may also raise the need to simultaneously integrate energy recovery technology into the PFD to keep the energy costs of the whole process as low as possible. How the prioritization between energy and water recovery is made is case dependent. However, MEBs provide the basis for follow-up marketability, technical, economic, and environmental assessments that will reduce the number of feasible PFDs stepwise.

3.4. Step 4: Marketability Assessment (Gate I)

The circular economy concept aims to transform value chains from linear to closed loop to promote a more environmentally friendly use of resources. The implementation of such a green economy however needs solid business models that create value from wastes that are reintroduced into societal consumption [69]. Despite the technological possibility of a WRF that recovers various resources from a given wastewater stream, its implementation may still be hindered by market-related bottlenecks which can introduce high uncertainties [22]. Consequently, after exploring possible PFDs and conducting MEBs to better understand their potential to recover resources and treat the wastewater, critical criteria for the value creation and marketability of recoverable resources need to be assessed for each PFD. The reason to assess the marketability conditions of each PFD at a fairly early process design step is that technical, economic, and environmental impact assessments require time and are costly and are therefore conducted in the next step. This way, only those processes showing promising marketability chances for the resources they recover will be assessed further, while processes that are not promising regarding marketability can be discarded already. We suggest to first assess seven criteria that may hinder a successful implementation of a technically feasible process (Table 3). The listed criteria should not be understood as final barriers but as challenges that have to be analyzed and addressed to implement innovative WRFs. At this early stage in the conceptual process design phase, the possibility of re-designing and adjusting a PFD to meet the assessment criteria is still possible if necessary. The proposed marketability assessment criteria are predominantly qualitative. To make the marketability of different PFDs comparable to each other, each criterion can be scored according to its expected performance. The balanced scorecard model invented by [70] is a useful multi-criteria analysis method, as it has already been adapted to be applied in technical process design [71] and even been used in assessing WWTP performance [27]. In the following, each criterion is further explained.

Table 3. Criteria to assess the marketability and value chain development potential of recoverable resources. Each criterion can be scored according to its expected performance.

Value Chain and Marketability Criteria	Explaining Remarks	Reference
Demand	Quantifying and localizing demands for recoverable resources	[72]
Logistics	Analyzing the distance, topography, and transport of recoverable resources to reach demand	[73]
Acceptance	Analyzing the customer acceptance for resources recovered from municipal wastewater	[7]
Legal situation	Analyzing regulations and policies that support or hinder the recovery of a resource	[74]
Supply potential	Estimating quantities of recoverable resources and relate them to the demand	[56]
Applications	Exploring and defining applications and utilization routes for recovered resources	[56]
Monetary value	Estimating the monetary value/market price of recoverable products	[22]

3.4.1. Demand and Logistics

As explained in the introduction, the end-of-waste concept proposes to recover resources from waste streams only if a clear market and demand exists [25]. Therefore, to proactively develop supply chains for recovered resources, the demand of potential customers needs to be quantified and located beforehand to decide on the required capacities and scales of recovery units. Spatial and temporal demand patterns need to be analyzed to decide on storage capacities and distribution lines for resources recovered from WRFs [72]. The latter aspect is especially valid for water reclamation for non-potable reuse that may be demanded with hourly, daily, and seasonal variations. Additionally, the distance to water users and the topographical location of the WRF, which is usually built downhill to use gravitational flows, might require uphill pumping, long distance pipeline construction, or other complex and costly transportation solutions [75]. To compare the logistic requirements implied by each PFD, the location of potential customers of resources can be mapped in detail using geographical information systems [76]. Demand side management is a method that can actively influence the demand patterns of consumers to fit the process output. Engaging the potential customers of recovered resources and analyzing collaboratively logistic bottlenecks can help to find fit-for-purpose solutions [72].

Ideally, the motivation of commercial customers to purchase recovered resources stems from a clear strategic advantage over conventional resources, like, e.g., from an increasing uncertainty in conventional resource purchase [77]. If conventional resource markets are volatile, long-term contractual agreements can provide security for commercial customers and therefore make them long-term partners. Long-term supply and demand contracts have been successfully established in other circular economy related fields, like, e.g., in the waste-to-energy domain [72]. Therefore, to approach potential commercial customers actively with the argument of long-term price stability may help to negotiate long-term agreements, which would in turn provide financial security for the WRF.

3.4.2. Acceptance of Customers

Stakeholder engagement is an essential part in step 2 where the objectives of the new WRF have been already reflected and agreed on. This must now be extended by including the viewpoints of potential customers of recoverable resources who are key stakeholders for a successful value chain development. Customers are either end-users or commercial companies that buy recovered resources to market them directly or to refine them further as a raw input material in their production process.

The acceptance of commercial customers and end-users is crucial as negative perceptions can be a major barrier for the successful marketing of resources recovered from wastewater [73]. To shift customer perceptions from fecal matter containing wastewater towards positive associations with resource recovery, they should be actively engaged during the design of a WRF to raise acceptance. The general goal should be that customers associate the plans with human morality, human interaction, and a feeling of participating in their community [78]. It is likely that some potential customers have already been represented in step 2, like, for example, the local community that would need to accept and trust intended water reclamation strategies. The acceptance of local customers can be improved by engagement campaigns that inform about the societal benefits of sustainable infrastructure in general but particularly of WRFs. If local end-users or commercial customers perceive the usage of locally recovered resources as a contribution to their community, acceptance is likely to increase [77]. For example, to underline that a planned WRF could reduce GHG emissions or provide opportunities for local economic growth is important to make end-users feel supportive of a more sustainable development in their direct environment [7].

If customers are local, nationwide, or even global, several examples show that without the conviction of end-users and commercial customers about the harmlessness of wastewater-derived resources, it would be complicated for any water utility to locate, finance, develop, and operate a WRF [79]. Only if customer needs are reflected and addressed early on in the planning process can vital trust and support be built [80]. Furthermore, the end-of-waste concept could provide the opportunity to bypass the acceptance barrier because it allows the labelling of recovered resources as full-fledged products instead of waste. As explained in the introduction, the end-of-waste status can only be applied if the recovery process of and the resource itself fulfil specified end-of-waste criteria. Therefore, it should be assessed here what is required for each resource intended to be recovered to be marketed as a product without the usually required information about its origin.

3.4.3. Legal and Policy Context

The concept of waste and its definition are far from obvious in different policies. The definition of waste as a non-useful material does not support the paradigm of the circular economy to perceive waste as a valuable resource. One aspect that hinders trading and thus the marketability of waste-derived products is the uncertain legal ownership of resources that are legally labelled as waste [81]. The end-of-waste concept proposes to recover resources from waste streams only if they comply with existing legislation and standards [25]. Therefore, it is worth including policymakers in the design process of WRFs and discussing to what extent recovered resources can be legally re-defined, what has to be done to do so, and which policies are missing in that context. Numerous examples show that legislation and policies including environmental regulations, subsidies, or other economic incentives can be discrete uncertainties for WRFs. For example, the application of P recovery technologies is especially relevant in countries where the agricultural reuse of sewage sludge is restricted by legislation [64]. Policy-driven P recovery can be expected to become more important in the EU as various member states including Germany introduce legislation to enforce P recovery from WWTPs [82]. The concern of legislators—that the recovered resources may be contaminated—can prevent necessary legislation allowing their marketing. One example is the prohibition in the European Union on using microbial protein produced from ammonia that has been recovered from municipal wastewater [83]. Although the ammonia is stripped from side streams as gas and therefore the microbial protein production system can be completely decoupled from the actual wastewater flows [84], it remains a legislative safety concern and is hence forbidden. Concerns over product harmlessness have also been exemplified in the long process of changing the Dutch fertilizer act to allow struvite marketing in the Netherlands [22].

These examples show that identifying and addressing legislative barriers and developing strategies to overcome them is crucial to successfully implement WRFs [23]. Addressing potential policy and legislative shortcomings for recoverable resources early is important, because clear policies provide economic security for the investors of recovered resource value chains. Therefore, it is important to include policy makers into stakeholder meetings and work collaboratively on necessary regulative changes. For example, it has been reported that subsidies can help to overcome the financial unattractiveness of water reclamation, which can be severe even though a clear need for regional water reuse exists [73]. Making decisions in WRF design despite complex and uncertain policy situations could be achieved by the method of dynamic adaptive policy making, which has been proposed for WRF implementation in the Dutch capital of Amsterdam. It follows a stepwise problem analysis, measure identification, and solution strategy to bring tailor-made policies in a way that enables the recovery and marketing of wastewater-derived resources [22].

3.4.4. Supply Potential and Applications

Compared to conventional production systems, only small quantities of a resource may be recoverable by a WRF. This can be due to the low yields of a recovery process, low resource concentrations in the side streams emerging from a process, or low overall resource quantities contained in the influent. Compared to industrial productions, the scalability of production is not given in waste-based systems and therefore the recovered product quantities might be comparably small, which can be a severe economic disadvantage [56]. The MEBs conducted in step 3 provide quantities of all resources that are recoverable by a process and can now be compared to the identified demands that are satisfied by conventional suppliers. In this way, it becomes clearer what supply potential the particular process can reach for a recovered resource and if it is competitive as a supplier in terms of quantities. If commercial demanders cannot become supplied sufficiently, the exploration of niche applications, as described by [85] for the case of biodegradable PHA as a niche within the biodegradable plastic market, may be crucial for certain resources to be competitive.

Combining wastewater fractions with other similar waste streams could increase the recoverable quantities of a product and therefore benefit from economy of scale [56]. Therefore, the possibility and usefulness of receiving other waste streams than municipal wastewater and acting also as a waste disposal facility should be investigated here. In particular, organic waste streams arising at different parts in the food supply chain could be processed in combination with the organic fraction of the wastewater. In Europe, ca. 20% of total food produced is wasted [86]. Circular solutions for food waste aim to recover a range of products that can also be recovered from wastewater, like e.g., volatile fatty acids or biopolymers [87]. It has also been shown that the co-digestion of sludge and organic municipal wastes to recover methane provides both environmental and economic benefits [88]. As explained above, people's acceptance of products recovered from wastewater can be a severe bottleneck. The range of possible applications for a recovered resource can be limited by the perception of stakeholders, and therefore applications that are not affected by this issue need to be explored creatively. For example, the marketing of consumer products that contain wastewater-derived resources is a challenge and therefore other applications should be preferred [3].

3.4.5. Monetary Value

Estimating the monetary of each resource recoverable by a process design is a necessary step for the cost–benefit analysis following in step 5. Together with the quantities estimated by the MEBs in step 3, the monetary value defines expectable revenues. Estimating market prices may give a first indication about which resource is preferably recovered compared to another. For example, given that the value of electricity and heat recovered by anaerobic COD digestion and subsequent methane combustion might be very low, alternative COD recovery technologies that lead to higher value products, like, e.g., biochemicals, might be recognized as preferable [8,56]. [22] provides an orientation for decision making in accordance with the monetary values of recoverable resources by introducing a value pyramid showing which recovery pathways are preferable over others in conflicting situations. The method suggests estimating the value of the recovered resources by considering monetary values, recoverable volumes, and markets targeted—like, e.g., the health and lifestyle market or the energy market.

3.5. Step 5: Multi-Criteria Assessment

After each PFD has been analyzed with MEBs and the marketability potential of the resources it aims to recover has been assessed, process designs with promising marketability chances will be assessed further in this step to estimate their performance in the technical, economic, and environmental dimension. It has been proclaimed that the fundamental shift from treatment towards resource recovery promises reduced operating costs and lower emissions [89]. However, a WRF also likely leads to new cost factors and emissions that do not exist in conventional WWTPs. Therefore, each PFD needs to be individually assessed considering the whole process using existing methodologies and applying a range of performance criteria. The first assessment aims to provide insights into the technical performance of a process, and only technically feasible process designs will then be assessed further by CBA to discard economically unfeasible designs. Finally, the environmental impacts of those process designs showing promising technical and economic performances will be assessed. During each of the three assessments, there is a chance to re-design a process if possible so that it copes with those criteria that turn out to be unsatisfying.

3.5.1. Technical Process Assessment (Gate II)

As described above, the shift from WWTPs towards WRFs requires that resource recovery technology integration becomes a central objective in process design; hence, technical decisions need to be guided to meet both treatment and recovery requirements. Therefore, the technical assessment will assess the performance of a process in the dimensions of (i) treatment, (ii) operation (Table 4), and (iii) resource recovery (Table 5). The MEBs conducted in step 3 provide the basis for estimating various technical performance criteria that are presented in Tables 4 and 5. The treatment performance of new processes is usually assessed by the removal efficiencies of pollutants that define the legal effluent quality, like, e.g., COD, TKN, and total phosphorous (TP) [35]. Since the environmentally safe release of treated water into surface water bodies remains the primary goal of designed processes, each process design has to be assessed accordingly. It is possible that effluent quality requirements will become stricter and ask for more indicator substances in the future. If that is expected, the treatment performance assessment can be extended by estimating the capability of a process to fulfil potential future legal requirements for micro-pollutants [43] and/or nutrient removal [32].

The integration of resource recovery technologies into treatment plants can imply operational uncertainties [26], and therefore the question about which technologies are most useful and how to combine them in process design has to be tackled [90]. Therefore, in addition to the treatment performance, the operation of each process design can be assessed. There have been criteria proposed and established for treatment process operation assessment which can be applied here [27,49,53]. Operational data and information for single process units, like, e.g., sedimentation tanks or bioreactors, can be extracted from the vast literature available on particular treatment technology operations [9,29,30]. Operational data for more innovative resource recovery units can be extracted from specific articles describing pilot or case studies. Searching the term "wastewater resource recovery technology" in an online search engine for scientific publications showed over 243,000 results in 2020.

After assessing the treatment performance and operation, each process can be assessed regarding its resource recovery performance, which includes criteria to assess the expectable quality of recovered resources on the one hand and the recovery efficiency of the process on the other hand. The end-of-waste concept proposes to facilitate recycling by defining that waste is no longer perceived as such if it has undergone a recovery process that ensures the use of a recovered product will not lead to overall adverse human health impacts [25]. Several studies have shown that resources recovered from municipal wastewater may be of uncertain quality or even contaminated, which may impose health risks. For example, struvite has been reported to possibly contain heavy metals [91], and reclaimed water may contain harmful by-products of chemical biocides used in tertiary water treatment [92]. Studies examining health risks in the field of circular economy seem mostly to deal with occupational health risks which relate to the workplace and less with health risks arising from recovered product use. In the context of WRFs, the only resource that has been subject to extensive risk management considerations is reclaimed water. Risks and therefore quality requirements for reclaimed effluents depend on the intended reuse type. Biological and human health safety control measures need to be proactively developed as legal standards are often missing for each reuse type [75]. Major concerns are pathogens that can cause acute infections at very low doses upon exposure, but also chemical micro-pollutants need to be removed from the water for safe reuse [93]. A systemic risk management approach that covers all aspects of the reclaimed water production, distribution, and utilization has been proposed but needs further elaboration and a proactive management approach [73,94]. To resolve legal uncertainties, the European Commission recently proposed minimum risk control standards for water reuse that can provide guidance for designing advanced treatment processes for safe-to-use reclaimed water [95]. The quality of a recovered resource should not only be safe for human health but also competitive with conventional alternatives on the market. After the potential applications and customers associated with a process have been analyzed in step 4, it is now important to assess whether a process can cope with the quality requirements of both. This can be a challenge, as it is one thing to recover a product from wastewater but another to obtain a marketable quality from the recovery process. For example, it is technically feasible to recover biochemicals like, e.g., volatile fatty acids (VFAs) or PHA from COD, but to obtain a certain purity requested from the industry is a technical challenge in mixed culture systems [8] and thus has to be considered from the early design stage on.

Next to resource quality, the resource recovery performance of a process can be assessed in terms of recovery efficiency. The mass efficiency of process designs can be assessed with the results of the mass and energy balances conducted in step 3. For example, if two different processes recover P but process (A) integrates struvite crystallization [96] while process (B) integrates the magnetic extraction of vivianite [97], it is useful to assess the recovery rate of the influent P of each process. Furthermore, if resource recovery technologies include not only the extraction but also on-site refinement of a recovered product, KPIs originally developed for the chemical or pharmaceutical process assessment could be applied to assess the performance of a particular recovery technology in comparison to an alternative one. For example, the chemical extraction of extracellular polymeric substances (EPS) from aerobic granular sludge is possible with different solvents [98] and could be assessed by the solvent score method [71].

Table 4. Criteria to assess the expectable technical performance of a process in the dimension's treatment and operation.

Treatment Performance Criteria	Explaining Remarks	Reference
Effluent quality	See Table 1	[35]
Future effluent quality	Capability to fulfil potential future legal requirements for micro-pollutants	[31]
	Capability to fulfil potential future legal requirements for nutrient removal	[32]
Process Operation Criteria	**Explaining Remarks**	**Reference**
Sludge treatment efficiency	Capability of a process to reduce suspended solids in sludge and its water content	[27]
Sludge production	The expected weight of excess sludge	[27]
Reagent efficiency	Estimate scores for chemicals used (e.g., metal-salts, polymers, methanol, etc.)	[27]
Energy efficiency	Expected net kWh to be consumed by the process	[27]
Exergetic efficiency	Energy useful for work in the process	[71]
Process safety	Potential hazard estimation (e.g., explosion risk)	[36]
Process robustness	Based on failure records, problem frequency, reliability of existing processes	[49]
Process flexibility	Susceptibility to shock loads of certain constituents	[35]
Equipment wear	Equipment wear (based on, e.g., operating hours, speed, load, start-ups)	[99]
SRT	Sludge retention time in days	[11]
HRT	Hydraulic retention time in hours	[11]
Reactor volume	Required sizes of units based on SRT and HRT	[11]
Contextual independence	Influence of external factors on the process performance (e.g., seasonal temperature)	[49]

Table 5. Criteria to assess the expectable technical performance of a process in the dimension resource recovery.

Resource Recovery Assessment Dimension	Recovery Criteria	Reference
Recovery process operation	Reliability of recovery process	[15]
	Process control requirements	[15]
	Operation simplicity	[15]
	Compatibility between different units (e.g., with treatment units)	[15]
	Process flexibility in certain parameters (e.g., oxygen availability, reaction time)	[15]
	Need for skilled staff	[15]
Quality of recovered resources	Reclaimed water (e.g., bacterial and viral indicators)	[92]
	Energy carrier (e.g., methane generation rate in biogas)	[100]
	Fertilizer (e.g., macro-nutrient content and plant availability, struvite contamination)	[64]
	Products (e.g., controlling the product spectrum in open culture volatile fatty acid fermentation)	[56]
Recovery efficiency	Mass efficiency (e.g., fraction of effluent that is reused)	[71]
	Mass intensity (mass of external raw materials in per mass of desired product out)	[101]
	Share of recovered energy used on-site	[102]
	Solvent score of a recovery unit	[71]
	Number of redox changes in a recovery unit	[71]

3.5.2. Cost–Benefit Analysis (Gate III)

After the technical assessment has been completed and processes with a technically unsatisfying performance have been either re-designed for improved performance or discarded as an unfeasible alternative, the economic performance of technically promising designs needs to be assessed. The European water framework directive demands that urban water systems should be economically self-sustained, meaning that costs should be covered by the system itself through water pricing and service fees for wastewater treatment [15]. Taking the latter into account, a WRF has a different "business model" compared to conventional WWTPs. Although its priority remains to treat wastewater and charge a fee for this environmental and human health service provision, a WRF ideally also generates revenues from recovered resource sales [90]. Resource recovery introduces new financial uncertainties and leads to a whole different cost–benefit structure within the wastewater treatment equation [22,37,103]. Not only are additional investment costs likely to occur from required recovery units and installations, but also substantial changes in operating costs can be expected if processes are designed from a resource recovery perspective. For example, integrating chemically enhanced primary treatment into a process that uses anaerobic sludge stabilization may alter the process economics in various ways. On the one hand, it promises economic benefits from increased methane yields and decreased aeration requirements for the biological treatment. On the other hand, it requires the usage of special polymers that represent an additional cost factor [67]. Another example would be the reclamation of reusable water accomplished by advanced membrane-based treatment. The additional treatment step leads on the one hand to additional operational costs for energy consumption [44], maintenance costs to prevent membrane fouling [104], and waste management costs for retentate handling [105]; on the other hand, it may generate steady economic benefits in the form of revenues from water customers [106]. Furthermore, P recovery requires additional investment costs but may also lead to lower waste management costs due to improved sludge dewaterability and benefits from recovered product marketing [97].

These examples show clearly that a reliable statement about the economic feasibility of a WRF can only be made if its combined costs and benefits are assessed. Therefore, this step aims to conduct a cost and benefit analysis which is a systematic approach for estimating and comparing the positive and negative economic consequences of an investment to determine its net profitability. It follows the simple formula (1):

$$NP = \sum Bi - \sum Ci, \tag{1}$$

where NP is net profit, B is the benefits of item i, and C is the costs of item i [34].

To assess the economic performance of processes, the time horizon that the new process is expected to be operated in needs to be defined. A 20-year time horizon to calculate the costs and benefits associated with wastewater resource recovery processes has been suggested [61,103], but it may be defined more accurately in accordance with site and project-specific circumstances. The economic performance of different process designs can only be compared if the same time horizon is applied in the assessment so that they have the same time to accumulate costs and benefits [107]. The costs and benefits that will arise during the expected time horizon are calculated for each process using the net present value (NPV). The NPV expresses the monetary value of future cash flows and is an indicator to determine the economic value of a process design and thus allows the ranking of alternatives. The higher the NPV, the more economically favorable a process design is. The NPV method requires the determination of a discount rate that accounts for the opportunity costs of time by discounting future costs and benefits because of the profit that could be earned in alternative investments. It is a widespread practice in CBA to use the current market interest rate as the discount rate [107]. The discount rate calculation is shown in formula (2). To calculate the NPV, the time horizon is usually divided into yearly periods and the net profits are discounted and calculated on a yearly basis, which leads to formula (3).

$$r = 1/(1+i)^n, \tag{2}$$

where the discount rate r equals the present value of 1€ received in n years when the interest rate i is compounded annually [107].

$$PV = \sum\nolimits_{t=0}^{n} \frac{NP_0}{(1+i)^0} + \frac{NP_1}{(1+i)^1} + \ldots + \frac{NP_n}{(1+i)^n}, \tag{3}$$

where the net present value (NPV) at time t, calculated for a time horizon of n years, is the sum of discounted annual net profits (NP), assuming a discount rate i. Adapted from [107].

Table 6 shows the cost and benefit factors to be included in CBA for a WRF process. The method required that all cost and benefit factors related to a process design are estimated for each year of the time horizon. The annual net benefits then need to be discounted and summed up to obtain the NPV of the process. To avoid the need of predicting future price level changes by, e.g., inflation, the costs and benefits should be expressed in current real prices and not with nominal prices [108]. Many occurring cost and benefit factors can be deduced from market prices or estimated using literature studies or expert judgement [64].

As in most infrastructure projects, a high initial total investment cost occurs at the beginning of the time horizon when the new process is planned, purchased, and constructed. A residual value of the fixed investments must be included within the investment costs occurring in the last year if the plant is believed not to be liquidated after the time horizon has ended. It reflects the capacity of the remaining service potential of fixed assets which are not yet completely exhausted [108]. The operational costs of wastewater treatment are usually measured on the basis of contaminant removal [33], which requires taking the influent characteristics into account that have been defined in step 1. Some cost factors may require general assumptions to keep a certain degree of simplicity during this early stage economic assessment. For example, the electricity needed to supply oxygen into biological treatment units depends on the saturation concentration of oxygen at an assumed temperature, pressure, and salinity [11]. Expectable benefits from resource sales can be calculated based on the quantities of recoverable resources that have been estimated for each process design in step 3 by MEBs and their market prices analyzed in step 4. In addition to resource sales, benefits could also be gained from charges for handling additional waste streams as explained in step 4, like, e.g., food wastes.

Costs and benefits are often defined in CBA as decreases and increases in human wellbeing, which can include various external effects of human behavior that have no market prize [34,51]. Although the monetization of these effects can be achieved by different methods [107], the cost and benefit factors suggested in Table 6 do not account for external effects like, e.g., the cost of undesirable effluent constituents entering surface water bodies. The reason is that the monetization of external effects is a complicated procedure usually conducted by experts like, e.g., environmental economists. This framework is supposed to be useful for institutions and decision makers in the wastewater sector that do not necessarily have a strong expertise in those specializations. The environmental impacts of a process will be carefully assessed in the next assessment stage. After the CBA has been completed for each process design, the results can be reconciled with the budget estimation conducted in step 1 to identify any variances between the available budget and the estimated costs of a process.

Table 6. Template for a complete cost and benefit analysis of water resource factory processes.

Investment Costs (IC)		**Year 1**	**Year 2**	**Year n**	**Reference**
IC1.	Planning				[36]
IC2.	Land acquisition				[15]
IC3.	Right of way				[103]
IC4.	Installations, e.g., buildings, reactors, pumps				[36]
IC5.	Construction and engineering				[36]
IC6.	Contingency				[103]
IC7.	Resource value chain creation (non-process assets)				
(a)	Vehicles to transport recovered resources				[36]
(b)	Pipelines to customers, e.g., reclaimed water				[73]
IC8.	Residual value (last year)				[108]
Total investment costs					
Operational costs (OC)					
OC1.	Labor				[36]
(a)	Operators				
(b)	Marketing and sales experts				
OC2.	Energy required from grid, e.g., electricity for aeration				[15]
OC3.	Maintenance				[103]
(a)	Inspections, repairs				
(b)	Replacements, e.g., membranes				
OC4.	Waste management				[15]
(a)	Sludge disposal				
(b)	Resource recovery related wastes, e.g., brines				
OC5.	Reagents and raw materials				[16]
(a)	For treatment, e.g., iron-salt, coagulants, carbon				
(b)	Resource recovery unit inputs, e.g., acids				
(c)	Packaging of recovered resources				
Total operational costs					
Periodic costs (PC)					
PC1.	Cost of financing, e.g., interests				[108]
PC2.	Fees, e.g., to regulatory authorities, insurances				[36]
Total periodic costs					
Benefits					
B1.	Service fees paid by the public for treatment				[37]
B2.	Subsidies for treatment or resource recovery				[36]
B3.	Resource value creation				[103]
(a)	Sales revenues resource x				
(b)	Sales revenues resource y				
(c)	Sales revenues resource z				
B4.	Charges for disposing other waste streams				[88]
Total benefits					
Annual net benefits					
Discount rate					
Annual discounted benefits					
NPV					

3.5.3. Environmental Impact Assessment (Gate IV)

Finally, after the technical and economic assessment has been completed and those process designs that did not perform well in one or both dimensions have been either re-designed for improved performance or discarded as unfeasible alternatives, the environmental impact of promising process designs can be assessed. It has been shown that overall, the environmental impact of WWTPs can be decreased through resource recovery implementation [17]. The growing possibilities of recovery technology integration into treatment processes implies that identifying the most environmentally friendly process alternative requires a careful impact assessment. Life cycle assessment (LCA) is a comprehensive and well-established method to analyze the environmental impact of products, services, and processes. The assessment embraces the entire system involved in the production, use, and disposal of a product or service under investigation. All environmentally relevant substances emitted, as well as extracted natural resources, can be identified and quantified in a "cradle to grave" approach [109]. LCA allows„ therefore making environmentally beneficial decisions at an early design stage and comparing process designs regarding their impacts. The execution of an LCA should follow a standardized methodology provided by The International Organization for Standardization's ISO 14000 and 14040 [110]. A recent review of LCA studies conducted for domestic wastewater treatment plants since the year 1990 concludes that the development of guidelines and standards is necessary to further shape a consistent LCA methodology for the field. For example, different functional units which serve as reference units in LCA are used in different studies which aggravates a comparison of already assessed treatment processes in the environmental dimension [111].

Since a WRF is in addition to a treatment process and also a production system, the system boundaries of a WRF process LCA will differ from a WWTP LCA, because the recovered and successfully marketed resources avoid the conventional production of similar goods [112]. The inclusion of these presumable positive impacts is achieved by the so-called approach of consequential LCA. To include the avoided impacts of substituted conventional goods into the assessment, assumptions have to be made on how they are produced. LCA databases provide readily defined impacts for a wide range of different conventional products and materials [113]. Other needed life cycling inventory data can be collected from published studies in the field of WWTP LCA [110,111]. Already available LCAs that include impacts associated with wastewater resource recovery mostly assess both energy recovery [114,115] and/or fertilizer recovery [116,117] as a consequence of different sludge handling technologies. In addition, the environmental impacts associated with nutrient recovery by aquatic species—like, e.g., algae [118]—and impacts associated with water reclamation and reuse have been a focus in wastewater treatment-related LCAs [119].

A conceptual scheme including relevant LCA impact categories of an LCA that assesses the combined impacts of operating a WRF process is drawn in Figure 3. It has been shown that the impacts of WWTPs mainly occur in the impact categories of (i) eutrophication and (ii) ecotoxicity in effluent receiving water bodies and (iii) global warming potential (GWP) due to sludge handling and electricity use [110]. In the following, we briefly describe those three impact categories and also which other aspects need to be taken into account when assessing the environmental impact of a WRF process. Since there are a variety of possible negative but also positive environmental impacts, only a complete assessment provides an overview of how an environmentally friendly process design performs in a certain impact category and in total. For more detailed information about the proposed impact categories, we refer to [120], who provide evaluation criteria and other requirements related to their application in LCA.

The impact category "eutrophication potential" is determined by the effluent concentrations of COD, P, and N that are released into the receiving water body [49]. They have ideally been estimated by the MEBs during step 3. Heavy metals and micropollutants responsible for ecotoxicity are probably more difficult to estimate due to the early design stage but especially in process designs that apply advanced treatment steps for indirect water reuse, the ecotoxicity impacts can be expected to be significantly lower compared to processes applying only secondary treatment [121].

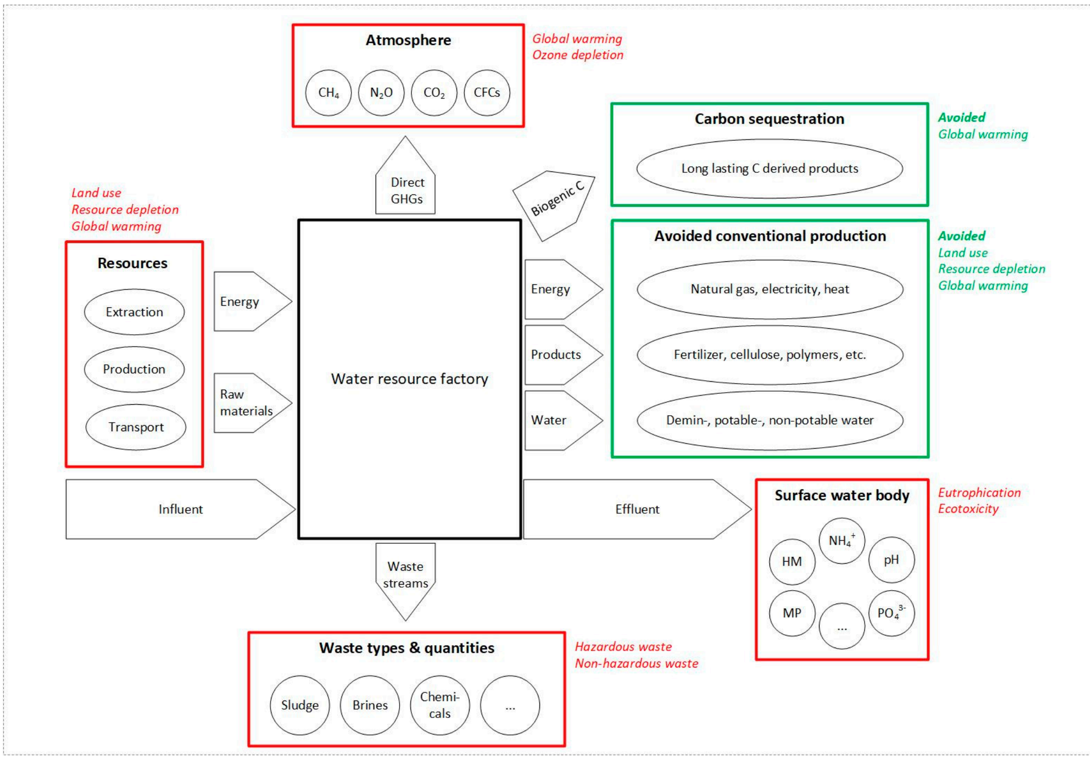

Figure 3. Environmental impacts that may occur due to the operation of a WRF. Negative impacts framed in red. Positive impacts are framed in green. Life cycle assessment (LCA) system boundaries are represented by the dashed line.

The most important emissions for the impact category "global warming potential" relate to the direct GHG emissions of CO_2, CH_4, and N_2O, which can occur at different treatment and resource recovery unit operations. Direct CO_2 emissions from aerobic and biological wastewater treatment are considered by the Intergovernmental Panel on Climate Change (IPCC) of biogenic origin and therefore can be excluded in the GWP estimations of WWTPs [122]. However, this might not be completely true as [123] showed that 4–14% of total organic carbon in municipal wastewater is from fossil origin, namely from synthetic products used in industrial and residential products. It is therefore debatable if this minor fraction of the total direct CO_2 emissions should be included in an LCA. WRFs may not only emit CO_2 but also sequester carbon as products recovered from COD, like, e.g., cellulose fibers, may store carbon long term when used as composite construction materials or in other long-lasting applications [124]. Even waste sludge that is finally disposed in landfills has already been accounted as a carbon sequestration method [125].

Furthermore, in contrast to direct CO_2 emissions, one has to account for direct CH_4 emissions as, these may represent a significant share of the overall GHG emissions of WWTPs and hence of WRFs. On a time scale of 100 years, CH_4 has a 28 times higher GWP relative to CO_2 [126], and therefore WRF process designers should be aware of potential direct emission sources and take preventative measures. To assess direct CH_4 emissions, several sources have to be considered. The most severe source (up to three quarters of the total CH_4 emissions of WWTPs) is anaerobic sludge digestion that leads, especially at low temperatures, to a high fraction of CH_4 remaining solubilized in the digestate, from where it can emit to the atmosphere. Those emissions may even exceed emissions avoided through energy recovery from biogas combustion. Therefore, appropriate digestate handling is important like, e.g., the capture of ventilation air applied to sludge handling processes for subsequent use as combustion air in combined heat and power generation [127]. A critical side stream that contains high amounts of dissolved CH_4 is the supernatant from digestate handling, which is usually recirculated into aerobic treatment units where the CH_4 is biologically oxidized to CO_2 by methanotrophics. This can be improved by different design and/or operation measures; the aeration rate should be high enough to sustain methanotrophic growth in the reactor but low enough to prevent CH_4 stripping. More CH_4 present in the reactor is beneficial for its aerobic conversion compared to low concentrations suggesting to merge CH_4 rich streams into aerobic treatment units; preferably use stirred-tank reactors over plug flow types [54]. In addition, the influent COD consists approximately of 1% CH_4 that has been produced by microbes in anaerobic zones in the sewer network. This should be taken into account in WRF design because the unit that enters the influent into the WRF should prevent intense contact with the ambient air. For example, screw conveyors imply a more intense contact than centrifugal pumps [122].

The third GHG that is directly emitted from a WRF is N_2O, which has been estimated to have a 265 times higher GWP than CO_2inn a 100 year time horizon [126]. The IPCC uses fixed emission factors to estimate N_2O emissions from WWTPs (e.g., 0.035 N_2O-N per kg^{-1} influent-TKN), but N_2O emissions depend strongly on the process design. Direct N_2O emissions are, in any case, relevant and hence should be minimized, and may occur at different unit operations that have either anoxic or aerobic zones. In aerobic treatment units, aeration may act as a stripping gas for N_2O [122]. Although microbial N_2O formation is associated with happening during anaerobic denitrification, more significant N_2O emissions occur during aerobic nitrification due to various species of ammonium oxidizing bacteria (AOBs). Partial nitrification that accumulates NO_2^- as an end product is probably the highest potential source that leads to N_2O formation [122], and therefore a process with integrated nitrification should be designed to prevent that. At low dissolved oxygen (DO) concentrations, the so-called nitrifier denitrification pathway may be used by particular autotrophic nitrifiers that not only oxidize NH_3 to NO_2^-, but also reduce NO_2^- to NO, N_2O, and N_2, which is optimally only happening in the denitrification process. Nitrifier denitrification contrasts therefore with coupled nitrification–denitrification, where many different organisms oxidize and reduce NH_3 to N_2 step wise [128]. In contrast, at high DO concentration, the so-called hydroxylamine pathway contributes to N_2O emissions in aerobic treatment units. During nitritation, NH_3 is first converted by AOBs to hydroxylamine (NH_2OH) and then to NO_2^-, and N_2O can be formed as a by-product during hydroxylamine oxidation. In addition, partial nitritation is another aerobic process often applied to treat side streams from, e.g., digestate handling, and may lead to N_2O emissions under low DO concentrations [122].

All in all, these examples show that direct GHG emission prevention by process design is complex and requires a good knowledge of microbial nitrogen and carbon conversion pathways under different operational conditions, like, e.g., differing DO concentrations. It might be difficult to quantify CH_4 and N_2O emissions accurately at this early design stage, but analyzing the potential critical point sources of a particular process design is necessary to consider emission prevention measures early. For example, choosing those reactor types that allow establishing a homogenous DO concentration in a critical process unit can already be considered at this early design stage to decrease the risk of N_2O emissions from aerobic treatment operations.

Another impact category to compare process designs is the amount of hazardous and non-hazardous waste leaving a process. However, we suggest to not include off-site waste handling in the assessment, because data about applied waste management practices of WRF wastes might be difficult to obtain if this is carried out by external companies. When data is available about external waste management practices, it is possible to extend the system boundaries to assess different options like, e.g., the destination of waste sludge (agricultural use, composting, landfill, incineration), which would all have different impacts [16].

In addition to the described direct environmental impacts of operation, emissions associated with the construction of a process should not be forgotten, as the resource intensity of construction may differ substantially between alternative designs. Those emissions need to be evenly distributed over the time horizon of a planned WRF. In contrast to construction, impacts related to end-of-life phase of a process are usually negligible compared to those from operation and construction [113]. Additionally, land degradation due to the plant construction might be accounted for since some processes are significantly more compact than others—e.g., aerobic granular sludge treatment would be preferable over conventional activated sludge in this impact category [129].

3.6. Step 6: Uncertainty Analysis (Gate V)

Since the design of most complex processes is based on a number of multidisciplinary data and premises mostly describing future events, only hypothesises can be made about the value of these data at the time at which design decisions are taken. These data are therefore subject to a certain degree of uncertainty and may be classified as intrinsic uncertain data (e.g., prices, market sizes), or evidence-based uncertain data (e.g., when different sources report different values for the same data), or data obtained from models to which a certain degree of uncertainty is associated (e.g., the estimation of physical properties from thermodynamic models) [26]. Analysing the uncertainty of input parameters in early stage WWTP design is necessary for better informed decision making. For example, as with any other predictions, estimating the costs and benefits of future actions holds uncertainty, and a reliable statement about the economic feasibility of a process can only be made after the uncertainties of cost and benefit estimations are analyzed [51]. During the LCA, the highest potential to introduce uncertainties to the assessment outcome is during the life cycle inventory where the inputs and outputs (e.g., energy requirements, wastes, GHG emissions) of a process are compiled and quantified [130].

To conduct an uncertainty analysis for each assessment stage individually, the uncertain assessment criteria need to be selected, and their uncertain domain needs to be defined before the domain can be sampled through a Monte Carlo analysis [11]. Defining the uncertain domain (the probability of occurrence in reality) of possible criteria variables can be achieved by using the program evaluation and review technique (PERT) distribution method. This method assigns a probability to three possible values considered for each criteria. The probability of occurrence in reality is not the same for all three values, as they are subjectively estimated by experts who define a minimum, a maximum, and a moderate value for each criteria (Formulas (4) and (5)). Experts are usually capable of giving a more confident guess about the probability of the moderate value than the extreme values, and hence it is given four times the probability weight of the minimum and maximum guess [51,131]:

$$\mu = \frac{\alpha + 4 * m + \beta}{6}, \tag{4}$$

$$\sigma = \frac{\beta - \alpha}{6}, \tag{5}$$

where the mean μ and the standard deviation σ of the PERT distribution are determined by the minimum value α, the most likely value m, and the maximum value β [51].

Once the uncertain criteria variables are selected and their uncertain domain is defined by PERT distribution, the domain can be sampled through Monte Carlo simulation. For example, 50 future scenarios with respect to realization of the chosen set of uncertain criteria variables applied in an assessment stage can be simulated to reveal the overall uncertainty of a process assessment dimension. In the simulation, it is assumed that no correlation exists among the assessment criteria. In this way, the Monte Carlo simulation helps decision making because it reveals which assessment criteria might need more data gathering to reduce uncertainties [51].

3.7. Step 7: Final Process Comparison and Selection

Each process design that passed the assessments in the four dimensions of marketability, technical feasibility, economic feasibility, and environmental impacts and shows a high probability that it meets the assessment specifications can now be subject to final comparison and selection. This final selection step should be carried out with the stakeholders on board that have been present during the objective definition in step 2 to ensure that all stakeholders agree with the outcome of the design procedure and commonly support the implementation of the finally selected process.

4. Conclusions

Water resource factories (WRFs) may recover water, energy, fertilizers, and other products from municipal wastewater and feed into a circular economy. The SPPD-WRF framework allows the strategic planning and design of a WRF step by step to finally obtain a process that is innovative, recovers marketable resources, is technically feasible, cost efficient, and shows low environmental impacts. By following the funnel and stage gating method, innovative WRF processes are assessed in multiple dimensions at an early design stage. This provides decision makers and process design engineers the possibility to re-design a WRF process and improve its performance during the actual process design phase. To meet the multidimensional requirements that WRFs need to fulfil, process performance criteria traditionally applied in WWTP design need to be extended by new criteria from other research fields, like, e.g., circular economy, industrial process engineering, project management, value chain development, and environmental impact assessment. After applying the SPPD-WRF framework, the process finally selected for implementation has been designed under careful consideration of the site-specific necessities and circumstances in which a new WRF has to operate. The necessity to replace an existing outdated WWTP with an innovative WRF needs to be clarified early, and drivers for more circular wastewater treatment practices, like, e.g., projected water scarcity or the need for emission reduction in current treatment processes, need to be identified. The following definition of process design objectives ideally includes all stakeholders to increase support while minimizing the resistance of critical stakeholders. Process flow diagrams need to be configured in a creative and multidisciplinary engineering team effort as resource recovery-oriented process configuration requires special technical expertise in fields beyond traditional wastewater treatment engineering. Each process configured then has to be analyzed by mass and energy balances, which are the basis to assess its performance further. The consequential process assessment and re-designing steps not only need to structure the process related design space but also the market related design space. Therefore, seven marketability criteria for recoverable resources are proposed in the SPPD-WRF framework to estimate the potential of an innovative WRF to recover marketable goods. This is novel in wastewater process design methodologies and aims to narrow down the number of technically possible WRF process designs to only those that are promising in terms of value chain development. Only those processes with promising marketability potential are assessed in greater detail regarding their technical performance. In addition to treatment performance criteria, this also includes criteria to assess the resource recovery potential of a process design. Quality criteria for recovered products to meet health and safety requirements but also specific customer expectations have to be considered here. WRF processes that show a technically promising performance are then further assessed by a cost–benefit analysis, which has to include not only investment-, variable-, and periodic costs but also expectable revenues from the recovered resource sales, which may have an important effect on the overall process costs. In a final assessment step, the environmental impacts of remaining process configurations have to be quantified using a life cycle assessment. In addition to direct process emissions, also consequential emissions related to avoiding the conventional production of successfully recovered resources are considered in the SPPD-WRF framework. With this strategical planning, process design, and assessment methodology, the framework provides decision makers in the urban water cycle with a practical tool to develop a WRF from a holistic perspective without compromising the primary goal of WRFs, which remains to produce good effluent qualities. Due to the multidimensionality of the framework, the finally selected WRF is more sustainable than conventional treatment processes that are usually designed with a rather narrow focus on treatment performance and costs. In addition, the SPPD-WRF framework provides guidance on organizing the recovery of resources in accordance with the main conditions of the end-of-waste concept, and therefore contributes to its application within the wastewater sector where it is yet underdeveloped [132].

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