Software Architecture Assessment for Sustainability: A Case Study

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Abstract. Software Architecture (SA) assessment provides an analysis of the quality of a high-level view of software-intensive systems, serving as a quality assurance mechanism. Sustainability is a crucial quality for digital ecosystems and as such, it presents assessment challenges due to the multi-dimensional nature of sustainability. This study addresses the challenge of sustainability assessment in SA. Due to a lack of guided sustainability assessment methods, we use an SA evaluation blueprint which we tailored for sustainability assessment. We use a blend of experience-based and quantitative assessment techniques for the assessment of design decision options. The SA assessment is performed on a case study integrating a SaaS-based solution, a learning management system called Canvas, within an educational institute. Our assessment provides an overview of trade-offs between design decision options. We use elements from an open-source toolkit (SAF Toolkit) and a Sustainability Impact Score (SIS) to identify the possible trade-offs and sustainability impacts across different sustainability dimensions. The assessment results identify the trade-offs between QAs and sustainability dimensions (mainly environmental) per design option. This information can help architects make informed decisions about sustainable design choices. Our evaluation method is designed to allow for the assessment of other SAs.

Keywords: software architecture · design decision · sustainability · software architecture assessment · software architecture evaluation · sustainability score · trade-off

1 Introduction

Software Architecture (SA) assessment is crucial for preventive quality assurance in the software development life cycle (SDLC). It is essential to ensure that the chosen architecture design decisions contribute to the quality of software. SA assessment serves as a means to assess quality at an early stage of SDLC, thereby reinforcing the significance of careful architecture planning in software development processes.

Lago *et al.* [17] put forward a case for treating sustainability as a software quality, allowing for comparisons with other quality attributes (QAs) for potential trade-offs. While maintainability is the most widely evaluated QA in SA assessment [9], sustainability can be viewed through the achievement of several QAs in combination, to support multiple sustainability dimensions (economic, environmental, social, and technical) [7].

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可持续性软件架构评估：案例研究

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抽象的。软件架构（SA）评估提供了对软件密集型系统的高级视图的质量分析，作为质量保证机制。可持续性是数字生态系统的一个关键品质，因此，由于可持续性的多维性质，它提出了评估挑战。本研究解决了南澳可持续性评估的挑战。由于缺乏指导性的可持续发展评估方法，我们使用为可持续发展评估量身定制的SA评估蓝图。我们结合使用基于经验和定量的评估技术来评估设计决策选项。 SA 评估是针对在教育机构内集成基于 SaaS 的解决方案（称为 Canvas 的学习管理系统）的案例研究进行的。我们的评估概述了设计决策选项之间的权衡。我们使用开源工具包（SAF 工具包）和可持续发展影响评分（SIS）中的元素来确定不同可持续发展维度上可能的权衡和可持续发展影响。评估结果确定了每个设计选项的质量保证和可持续性维度（主要是环境）之间的权衡。这些信息可以帮助建筑师就可持续设计选择做出明智的决定。我们的评估方法旨在允许评估其他 SA。

关键词：软件架构・设计决策・可持续性・软件架构评估・软件架构评估・可持续性得分・权衡

1 介绍

软件架构 (SA) 评估对于软件开发生命周期 (SDLC) 中的预防性质量保证至关重要。确保所选的架构设计决策有助于软件质量至关重要。 SA 评估是在 SDLC 早期阶段评估质量的一种手段，从而强化了软件开发过程中仔细架构规划的重要性。

拉戈等人。 [17] 提出了将可持续性视为软件质量的案例，允许与其他质量属性（QA）进行比较以进行潜在的权衡。虽然可维护性是 SA 评估中评估最广泛的 QA [9]，但可持续性可以通过组合实现多个 QA 来看待，以支持多个可持续性维度（经济、环境、社会和技术）[7]。

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While several case studies exist on the SA assessment for different QAs such as maintainability, performance, availability [4,8], the sustainability assessment case studies are only carried out in the context of maintainability and evolvability QAs [14,18,19].

In our review of SA assessment methods, we observed a lack of SA assessment methods or their application for sustainability [9]. We identified a gap in trade-off analysis across 4D-sustainability. Using the findings and data from this work, we developed an SA evaluation blueprint tailored for sustainability assessment [10]. In this study, we instantiate this blueprint and apply it to assess the design decisions for sustainability. We aim to answer the research question, ***"How to guide software architects in assessing SA for sustainability?"*** We carry out the SA assessment on the integration of Canvas, a learning management system (LMS) at an educational institute. We leverage the expertise of the architects at the educational institute to perform experience-based SA assessment by analyzing the relevant design decisions for their sustainability.

The results of this study provide, (i) a step-by-step guide with specific techniques for SA assessment for sustainability, (ii) Sustainability-Quality Model (SQ Model) [5] representing dependency of sustainability dimension on QAs, (iii) Dependency Matrix (DMatrix) [6] identifying the relationship between QAs and their trade-offs, and (iv) Sustainability Impact Score (SIS) for sustainability support per design decision option. We further elaborate on the implications of our results, challenges, and future directions.

2 Background

In this section, we define the background knowledge of the research area. We define software sustainability in general and then contextualize it for SA. We also provide contextual information about our case study subject.

Software Sustainability. Sustainable development is defined as meeting 'the needs of the present without compromising the ability of future generations to meet their own needs' [3]. In the context of software, Venters *et al.* [21] link this 'need' to the time dimension of sustainability, *i.e.,* evolution of software due to changing requirements of stakeholders over time causing direct, enabling, and systemic impacts [12]. Lago *et al.* [17] represent sustainability across four dimensions; economic, environmental, social, and technical. Further, the definition is elaborated as "the preservation of the beneficial use of digital solutions, in a context that continuously changes" [16]. Hence, the notion of change makes sustainability assessment of digital solutions, imperative.

Software Architecture and Sustainability. Architecture sustainability is defined as the ability of the architecture to endure changes throughout the SDLC [1]. These changes can stem from shifts in requirements and business goals, operating environment, and technologies. In software architecture, sustainability refers to both (i) Architecture Knowledge Sustainability, *i.e.,* preservation of architecture knowledge with continuous change *e.g.,* consistency of architecture views, rationalization completeness, requirement fulfillment, change scenario robustness, and decision traceability [19], and (ii) Sustainability through Architecture Practices, *i.e.,* the adoption of SA practices that enable the development of a sustainable software product, *e.g.,* tactics from Vos *et al.* [22] like edge computing, using spot instances, auto-scaling, etc.. In this study, we focus on the latter.

虽然针对不同 QA（例如可维护性、性能、可用性）的 SA 评估存在一些案例研究[4,8]，但可持续性评估案例研究仅在可维护性和可演化性 QA 的背景下进行[14,18,19]。

在我们对 SA 评估方法的审查中，我们发现缺乏 SA 评估方法或其在可持续性方面的应用 [9]。我们发现了 4D 可持续性权衡分析中的差距。利用这项工作的发现和数据，我们开发了一个针对可持续性评估量身定制的 SA 评估蓝图 [10]。在本研究中，我们实例化了该蓝图并将其应用于评估可持续性的设计决策。我们的目标是回答这个研究问题：“如何指导软件架构师评估软件架构的可持续性？”我们对教育机构的学习管理系统 (LMS) Canvas 的集成进行 SA 评估。我们利用教育机构建筑师的专业知识，通过分析相关设计决策的可持续性来执行基于经验的 SA 评估。

本研究的结果提供了：(i) 可持续发展 SA 评估具体技术的分步指南，(ii) 可持续发展质量模型（SQ 模型）[5]，代表可持续发展维度对 QA 的依赖性，(iii)) 依赖矩阵 (DMatrix) [6] 确定 QA 及其权衡之间的关系，以及 (iv) 针对每个设计决策选项的可持续性支持的可持续性影响评分 (SIS)。我们进一步阐述了我们的结果、挑战和未来方向的影响。

2 背景

在本节中，我们定义研究领域的背景知识。我们对软件可持续性进行总体定义，然后将其融入软件应用的情境中。我们还提供有关案例研究主题的背景信息。

软件可持续性。可持续发展被定义为“满足当代人的需求而不损害子孙后代满足其自身需求的能力”[3]。在软件方面，Venters 等人。 [21]将这种“需求”与可持续性的时间维度联系起来，即，由于利益相关者的需求随着时间的推移而变化，导致软件的演变，从而造成直接的、有利的和系统性的影响[12]。拉戈等人。 [17] 代表四个维度的可持续性；经济、环境、社会和技术。此外，该定义被阐述为“在不断变化的背景下保留数字解决方案的有益用途”[16]。因此，变革的概念使得数字解决方案的可持续性评估势在必行。

软件架构和可持续性。架构可持续性被定义为架构在整个 SDLC 中承受变化的能力[1]。这些变化可能源于需求和业务目标、操作环境和技术的变化。在软件架构中，可持续性指的是（i）架构知识可持续性，即在持续变化的情况下保存架构知识，例如架构视图的一致性、合理化完整性、需求满足、变更场景稳健性和决策可追溯性[19]，以及（ii) 通过架构实践实现可持续性，即采用 SA 实践来开发可持续软件产品，例如 Vos 等人的策略。 [22]比如边缘计算、使用点实例、自动缩放等。在本研究中，我们重点关注后者。

Case Study Subject - *Canvas*. Canvas is a learning management system (LMS) developed by Instructure[1]. It supports online and blended learning environments to create, manage, and deliver academic content. Canvas is an off-the-shelf software-as-a-service (SaaS) solution integrated with an educational institute's internal authentication and information system. Third-party learning and teaching tools are integrated with Canvas through a Learning Tools Interoperability (LTI) interface. The details of the SA components can be found in our replication package [11] (under `/docs`). We use this case of Canvas integration as a subject for SA assessment to support the educational institute for its new sustainability reporting requirements (See Sect. 5-II).

3 Related Work

Extensive work has been done in SA assessment with methods like ATAM [13], and SARA [20]. This section outlines the existing work in SA assessment specifically for sustainability and identify the focus areas and gaps.

Koziolek *et al.* [14] present MORPHOSIS, a metric-based SA evaluation method for sustainability assessment at the source code level. They use Architecture Level Modifiability Analysis (ALMA) [2] as an underlying evaluation technique. Their approach tracks architecture-level metrics for evolution scenarios and focuses on modifiability, reusability, modularity, and testability metrics. Sehestedt *et al.* [19] evaluate SA sustainability using architecture-level quantitative metrics, defining sustainability as maintainability and evolvability. Their 4C criteria (completeness, consistency, correctness, clarity) assess architecture models, decisions, and requirements, focusing on decomposition quality, best practice adherence, view consistency, rationalization completeness, requirement fulfillment, change scenario robustness, and decision traceability. The evaluation focuses directly on *Architecture Knowledge Sustainability*. Ojameruaye *et al.* [18] present an SA evaluation based on Cost Benefit Analysis Method (CBAM), Portfolio theory, and Technical Debt, linking architecture assessment to system goals. They provide a desirability rating for each architecture strategy for realistic cost-benefit analysis, helping identify risk and debt-based trade-offs across five sustainability dimensions.

The current SA assessments for sustainability focus on either, the sustainability of architecture at the source code level or the sustainability of the documented architecture knowledge, *i.e.,* models, views, and requirements. Quantification-based techniques like architecture metrics or ratings are used. None of these methods analyze the high-level architecture (e.g. at the level of architecture views or design decisions) and the implications of the chosen decisions on sustainability, *i.e.,* having positive or negative effects on different sustainability dimensions. Our study evaluates design decisions based on prioritized evaluation criteria, *i.e.,* QAs for sustainability. We use a mix of experience-based and quantitative approaches.

4 Study Design

We describe the goal of our study based on the template, as shown in Table 1. We use the SA evaluation blueprint [10] as a guide to carry out the SA assessment. The SA assessment requires, as major input (i) Architecture Documentation, (ii) Tacit Knowledge of

[1] https://www.instructure.com/canvas.

案例研究主题 - 画布。 Canvas 是 Instruct 开发的学习管理系统 (LMS)。它支持在线和混合学习环境来创建、管理和交付学术内容。 Canvas 是一种现成的软件即服务 (SaaS) 解决方案，与教育机构的内部身份验证和信息系统集成。第三方学习和教学工具通过学习工具互操作性 (LTI) 接口与 Canvas 集成。 SA 组件的详细信息可以在我们的复制包 [11]（位于 /docs 下）中找到。我们使用 Canvas 集成的案例作为 SA 评估的主题，以支持教育机构新的可持续发展报告要求（参见第 5-II 节）。

3 相关工作

使用 ATAM [13] 和 SARA [20] 等方法在 SA 评估方面已经进行了大量工作。本节概述了专门针对可持续性的 SA 评估的现有工作，并确定了重点领域和差距。

科齐奥莱克等人。 [14]提出了 MORPHOSIS 一种基于度量的 SA 评估方法，用于源代码级别的可持续性评估。他们使用架构级可修改性分析 (ALMA) [2] 作为基础评估技术。他们的方法跟踪演化场景的架构级指标，并重点关注可修改性、可重用性、模块化和可测试性指标。塞赫斯特等人。 [19]使用架构级定量指标评估SA可持续性，将可持续性定义为可维护性和可演化性。他们的 4C 标准（完整性、一致性、正确性、清晰度）评估架构模型、决策和需求，重点关注分解质量、最佳实践遵守、视图一致性、合理化完整性、需求满足、变更场景稳健性和决策可追溯性。评估直接关注建筑知识的可持续性。奥贾梅鲁耶等人。 [18]提出了基于成本效益分析方法（CBAM）、组合理论和技术债务的 SA 评估，将架构评估与系统目标联系起来。它们为每个架构策略提供了可取性评级，以进行实际的成本效益分析，帮助识别五个可持续发展维度上的风险和基于债务的权衡。

当前的 SA 对可持续性的评估侧重于源代码级别架构的可持续性或记录的架构知识（即模型、视图和需求）的可持续性。使用基于量化的技术，例如架构指标或评级。这些方法都没有分析高层架构（例如，在架构视图或设计决策层面）以及所选决策对可持续性的影响，即对不同可持续性维度的积极或消极影响。我们的研究根据优先评估标准（即可持续性的质量保证）评估设计决策。我们结合使用基于经验和定量的方法。

4 研究设计

我们根据模板描述了我们的研究目标，如表1所示。我们使用SA评估蓝图[10]作为指导来进行SA评估。 SA 评估要求主要输入 (i) 架构文档，(ii) 的隐性知识

[1] https://www.instructure.com/canvas.

Table 1. Goal of the study—Wohlin *et al.* [23]

Analyze	Software Architecture of an LMS
For the purpose of	Assessment
With Respect to	Sustainability
From the point of view of	Software Architects
In the context of	An Educational Institute

Architects, and (iii) QAs as evaluation criteria. The expected output of this evaluation is information about inter-QA tradeoffs and inter-sustainability-dimension trade-offs for design concerns. As a side product of this study, we also get an instantiation (step-by-step method) of the SA evaluation blueprint for sustainability in the form of concrete steps, which can be used for other SA assessments. Two experts were chosen for this case study, both working as solution architects at the educational institute for 6 years with an approximate total of 17 years of experience working in IT. Experts were chosen based on their experience, knowledge of the system, and availability. One of the experts has worked for the educational institute for 17 years and proved to be a rich resource for tacit knowledge. We asked both experts questions regarding the input elements to drive each phase of the SA assessment. The authors of this study facilitated the evaluation process and performed the quantitative analysis which was again discussed with the experts. The quantitative analysis was performed by defining a Sustainability Impact Score (see Eq. 1) supported by the elements of the SAF Toolkit (via D-Matrix).

5 Study Execution and Results

The SA evaluation blueprint [10] provides a set of eleven general steps to support the sustainability assessment process. It is independent of the techniques used in each step, *e.g.,* the techniques for identification of approaches, prioritization, generation, and evaluation of data. In our study, we elaborate on each step of the blueprint and provide step-by-step details of the execution of each step. We use a mix of experience-based and quantitative techniques. Figure 1 shows the SA assessment steps from the blueprint in the middle together with the inputs and outputs (I/O) of our case study. The steps are tagged with specific techniques used (experience-based and quantitative), and the sustainability perspective is injected in each step.

I. Preparation. In the preparation phase, the authors met with the management of the project to discuss the proposed SA assessment and their expectations. Together we selected the relevant experts from the project for their expertise. We prepared a slide set for the explanation of the study execution and presented it to all involved stakeholders.

II. Requirement Identification. In this phase, we identified the requirements of the SA assessment, *i.e.,* the evaluation criteria. We identified the QAs for SA of Canvas integration from the technical requirements document. These QAs were checked for their

表 1. 研究目标——Wohlin 等人。[23]

分析	LMS 的软件架构
为了	评估
关于	可持续发展
从以下角度来看	软件架构师
在这样的背景下	教育机构

建筑师，以及 (iii) QA 作为评估标准。该评估的预期输出是有关设计问题的质量保证间权衡和可持续性维度间权衡的信息。作为本研究的副产品，我们还以具体步骤的形式获得了可持续发展的 SA 评估蓝图的实例（逐步方法），可用于其他 SA 评估。本案例研究选择了两名专家，两人都在教育机构担任了 6 年的解决方案架构师，拥有大约 17 年的 IT 工作经验。专家的选择是基于他们的经验、系统知识和可用性。其中一位专家已在该教育机构工作了17年，事实证明他拥有丰富的隐性知识资源。我们向两位专家询问了有关驱动 SA 评估每个阶段的输入要素的问题。本研究的作者促进了评估过程并进行了定量分析，并再次与专家进行了讨论。通过定义由 SAF 工具包要素（通过 D 矩阵）支持的可持续性影响评分（参见公式 1）来进行定量分析。

5 研究执行和结果

SA 评估蓝图 [10] 提供了一组十一个一般步骤来支持可持续性评估过程。它独立于每个步骤中使用的技术，例如用于识别方法、确定优先级、生成和评估数据的技术。在我们的研究中，我们详细说明了蓝图的每个步骤，并提供了每个步骤执行的分步细节。我们结合使用基于经验和定量的技术。图 1 显示了中间蓝图的 SA 评估步骤以及我们案例研究的输入和输出 (I/O)。这些步骤都标有所使用的特定技术（基于经验和定量），并且每个步骤都注入了可持续性观点。

一、准备工作。 在准备阶段，作者与项目管理层会面，讨论拟议的 SA 评估及其期望。我们一起从该项目中挑选了具有专业知识的相关专家。我们准备了一套幻灯片来解释研究执行情况，并将其呈现给所有相关利益相关者。

二.需求识别。 在这个阶段，我们明确了SA评估的要求，即评估标准。我们从技术要求文档中确定了 Canvas 集成 SA 的 QA。这些 QA 均经过检查

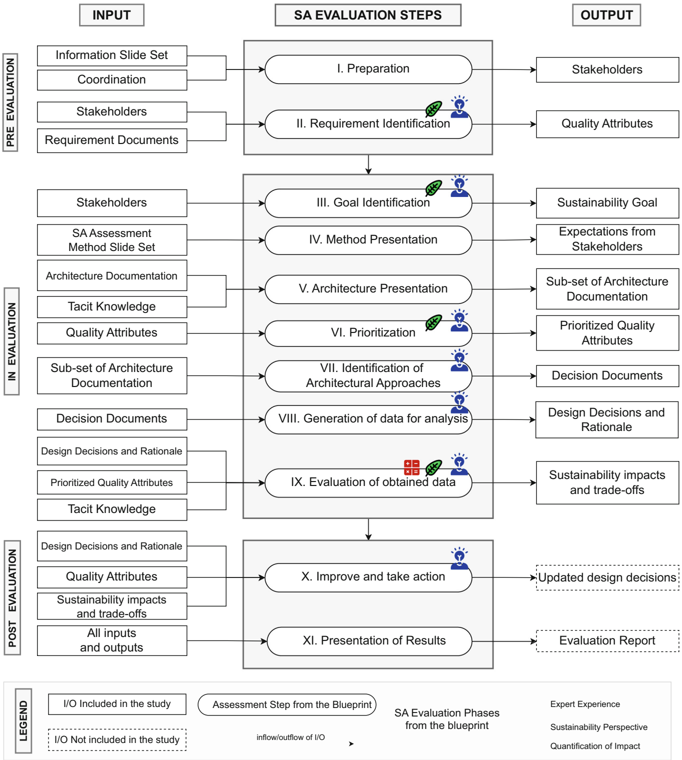


Fig. 1. Instance of the SA Evaluation Blueprint in [10]

relevance with input from the experts. The management team at the educational institute requested a sustainability requirement to be added for the procurement of Canvas as an LMS, to comply with the future EU regulations for reporting carbon emissions[2]

Hence, the educational institute aims to identify the sustainability-related improvement points on which they require support internally, or from Canvas. We suggested resource utilization as an additional QA for this research. The final list of QAs was identified in consultation with the experts and management team at the educational institute.

III. Goal Identification. The goal of this SA assessment was a sustainability assessment of the Canvas integration with the information system at the educational institute. We treated Canvas itself as a single black box component. We did not analyze the SA of the sub-components inside Canvas.

IV. Method Presentation. We presented the SA assessment method to the experts to explain all the steps and information needed from them during a one-hour meeting ses-

[2] https://consilium.europa.eu/en/press/press-releases/2024/02/05/environmental-social-and-governance-esg-ratings-council-and-parliament-reach-agreement/.

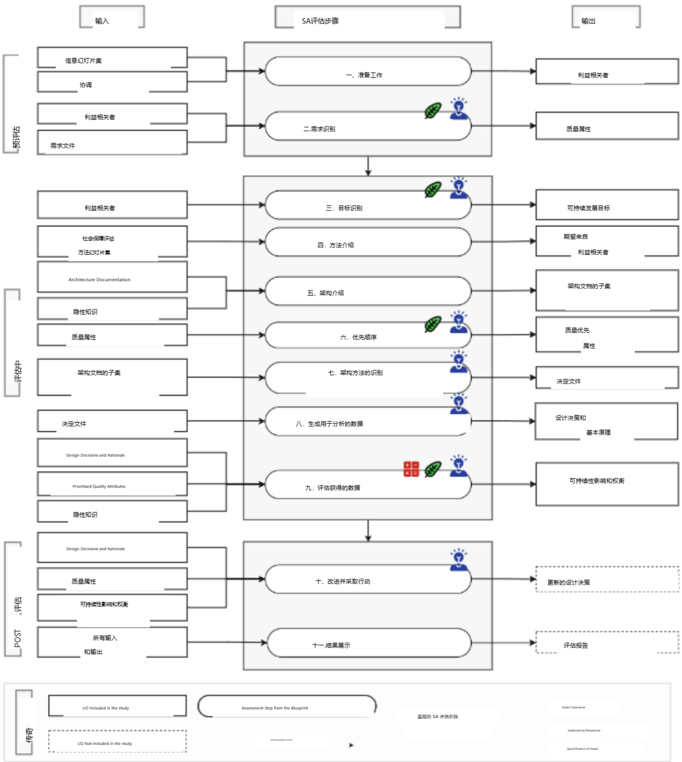


图 1. [10]中 SA 评估蓝图的实例

我们根据技术要求文档的相关性和专家的意见确定了 Canvas 集成 SA 的 QA。该教育机构的管理团队要求在采购 Canvas 作为 LMS 时添加可持续性要求，以符合未来欧盟报告碳排放的法规

因此，教育机构的目标是确定他们需要内部或 Canvas 支持的与可持续发展相关的改进点。我们建议资源利用作为本研究的额外质量保证。最终的质量保证清单是在与教育机构的专家和管理团队协商后确定的。

三．目标识别。本次 SA 评估的目标是对 Canvas 与教育机构信息系统的集成进行可持续性评估。我们将 Canvas 本身视为一个黑盒组件。我们没有分析Canvas内部子组件的 SA。

四．方法介绍。 我们向专家们介绍了 SA 评估方法，并在一小时的会议中解释了他们需要的所有步骤和信息。

[2] https://consilium.europa.eu/en/press/press-releases/2024/02/05/environmental-social-and-gov ernance-esg- ratings-council-and-parliament-reach-agreement/。

sion. In this session, we exchanged information and communicated the expectations from both ends about the SA assessment.

V. Architecture Presentation. The experts presented the SA as a component diagram (see `/docs` [11]) and explained all the components, their interconnections, and the functionality they support. The experts also shared internal documentation. As the original documentation was in Dutch, we translated the documents using Google Translate. The experts being native Dutch speakers helped resolve any discrepancies in translation for the correctness of technical and contextual information.

VI. Prioritization. The SA evaluation blueprint [10] presents two types of prioritization. At first, we performed *prioritization of evaluation criteria*. It involved an iterative process wherein two experts (*i.e.,* architects) were consulted. These evaluation criteria were defined by the QAs identified in Step II. Initially, we presented the experts with the list of QAs with their respective definitions sourced from the documentation. The experts ranked the QAs, placing the most important ones at the top and the least important at the bottom (see Table 2). Through mutual discussion concerning the role of QAs for the SA, adjustments to the prioritization of QAs were made. Once the QAs were prioritized, a sustainability-specific QA 'resource utilization', was introduced. The experts determine the placement of this new QA considering its possible trade-offs with high-priority QAs, at rank 4 (1 = lowest). During this prioritization process, some resource-intensive scenarios were also identified where the high-priority QAs are vital.

Table 2. Prioritized Evaluation Criteria

Quality Attribute	Priority Rank (13 = highest)
Availability	13
Scalability	12
Time Behavior	11
Security	10
Interoperability	9
Portability	8
Modifiability	7
Reliability	6
Testability	5
Resource Utilization	4
Analysability	3
Modularity	2
Reusability	1

QA definitions are available in Online Material (`/data/sqmodel.xlsx`) [11]

锡安。在本次会议中，我们交换了信息，传达了双方对SA评估的期望。

五、架构介绍。专家们将 SA 作为组件图呈现（参见 /docs [11]），并解释了所有组件、它们的互连以及它们支持的功能。专家们还分享了内部文件。由于原始文档是荷兰语，我们使用谷歌翻译翻译文档。母语为荷兰语的专家帮助解决了翻译中的任何差异，以确保技术和上下文信息的正确性。

六. 优先顺序。 SA 评估蓝图 [10] 提出了两种类型的优先级。首先，我们对评价标准进行了优先排序。它涉及一个迭代过程，其中咨询了两名专家（即建筑师）。这些评估标准由步骤 II 中确定的 QA 定义。最初，我们向专家提供了 QA 列表以及来自文档的各自定义。专家们对 QA 进行了排名，将最重要的问题放在顶部，将最不重要的问题放在底部（见表 2）。通过关于 QA 在 SA 中的作用的相互讨论，对 QA 的优先级进行了调整。一旦确定了质量保证的优先级，就引入了针对可持续发展的质量保证“资源利用”。专家们考虑到与高优先级 QA 的可能权衡，确定了新 QA 的位置，排名为 4（1 = 最低）。在此优先级确定过程中，还确定了一些资源密集型场景，其中高优先级 QA 至关重要。

表 2. 优先评估标准

质量属性	优先级（13 = 最高）
可用性	13
可扩展性	12
时间行为	11
安全	10
互操作性	9
可移植性	8
可修改性	7
可靠性	6
可测试性	5
资源利用	4
可分析性	3
模块化	2
可重复使用性	1

在线材料中提供了 QA 定义（/data/sqmodel.xlsx）[11]

VII. Identification of Architecture Approaches. We utilized the tacit knowledge of the experts to explore the documentation, choose an architecture view to start our research and identify the documents useful for our goal. We used their expertise to extract architecture design decisions from the documents and their experience to validate the extracted data and its relevance to the architecture. The existing documentation included (i) Component diagrams (ii) Decision Documents (not necessarily architecture) (iii) Other documents about requirements, scenarios, procurement needs, etc.. We read these documents and use the tacit knowledge of the experts to understand the available artifacts. The *Decision Documents* are system-wide decision documents with decision information about the functional, non-functional, UI-specific, and architecture aspects. Further, the scenarios identified during the prioritization steps were used to list design concerns and their respective design options for those scenarios.

VIII. Generation of Data for Analysis. In this step, we extracted design decisions from the identified architecture approaches which acted as data for evaluation.

Creating a Design Decision Template. To document the design decisions consistently, we created a template based on, (i) information available in documents and (ii) information needed for evaluation, *e.g.,* QAs, IDs (see data/DD_Template.xlsx [11]).

Data Extraction. We extracted information mainly from the decision documents of the system into the Design Decision Template. For information extraction, we only used decision documents flagged for architecture advice in the internal dashboard documents. We used other documents for finding contextual information about the design decisions (*e.g.,* about a specific functional requirement or goals, requirements behind a certain decision, relevant scenarios, etc..).

Populating the Template. We populated the information from these decision documents into our template as nine design decisions. The extracted elements included (i) design concern, (ii) design options, (iii) the rationale per design option, (iv) issues (if any), (v) supported QAs, and (vi) chosen decision. As the documents under analysis were not in a single template or format, our strategy ensured a systematic recovery of design decisions for effective SA assessment. We used the knowledge and expertise of the experts to identify the QAs (from Table 2) supporting each design option.

Validation of Data. The nine extracted decisions were validated by the experts as being correct and having architectural implications. We gathered feedback from the experts for each step of data generation and analysis going forward.

IX. Evaluation of Obtained Data. The extracted design decisions were used as input for this step. We used a combination of two techniques, (i) Experience-based technique – by using feedback from the experts for analyzing alternatives and trade-offs, and (ii) Quantification-based technique – by using elements of open source SAF Toolkit [15] and Sustainability Impact Score (SIS) to identify sustainability impact.

SQ Model. We use the QAs from Table 2 to build a Sustainability Quality (SQ) Model [7] as shown in Table 3. The SQ model helps map the QAs to 4D-sustainability; Economic

七．架构方法的识别。 我们利用专家的隐性知识来探索文档，选择架构视图来开始我们的研究并确定对我们的目标有用的文档。我们利用他们的专业知识从文档中提取架构设计决策，并利用他们的经验来验证提取的数据及其与架构的相关性。现有的文档包括（i）组件图（ii）决策文档（不一定是架构）（iii）其他有关需求、场景、采购需求等的文档。我们阅读这些文档并利用专家的隐性知识来理解可用的工件。决策文档是系统范围的决策文档，其中包含有关功能、非功能、特定于 UI 和架构方面的决策信息。此外，在优先级划分步骤中确定的场景用于列出设计问题以及这些场景各自的设计选项。

八．生成用于分析的数据。在此步骤中，我们从已识别的架构方法中提取设计决策，作为评估数据。

创建设计决策模板。为了一致地记录设计决策，我们基于 (i) 文档中可用的信息和 (ii) 评估所需的信息（例如 QA、ID）创建了一个模板（请参阅 data/DD_Templatexlsx [11]）。

数据提取。我们主要从系统的决策文档中提取信息到设计决策模板中。对于信息提取，我们仅使用内部仪表板文档中标记为架构建议的决策文档。我们使用其他文档来查找有关设计决策的上下文信息（例如，有关特定功能要求或目标、特定决策背后的要求、相关场景等）。

填充模板。我们将这些决策文档中的信息作为九个设计决策填充到我们的模板中。提取的要素包括 (i) 设计问题、(ii) 设计选项、(iii) 每个设计选项的基本原理、(iv) 问题（如果有）、(v) 支持的 QA 和 (vi) 所选决策。由于所分析的文档不采用单一模板或格式，因此我们的策略确保系统地恢复设计决策，以进行有效的 SA 评估。我们利用专家的知识和专业知识来确定支持每个设计选项的质量保证（来自表 2）。

数据验证。专家们验证了九个提取的决策是正确的并且具有架构意义。我们收集了专家对未来数据生成和分析每个步骤的反馈。

九．评估获得的数据。提取的设计决策用作此步骤的输入。我们结合使用了两种技术，(i) 基于经验的技术 – 通过使用专家的反馈来分析替代方案和权衡，以及 (ii) 基于量化的技术 – 通过使用开源 SAF 工具包的元素 [15]可持续发展影响评分 (SIS) 以确定可持续发展影响。

SQ 型号。我们使用表 2 中的 QA 构建可持续性质量 (SQ) 模型 [7]，如表 3 所示。SQ 模型有助于将 QA 映射到 4D 可持续性；经济的

(Ec), Environmental (En), Social (S), and Technical (T). This mapping helps us understand how each QA can have an impact across one or more sustainability dimensions. This is essential to observe inter-dimension sustainability trade-offs. It is important to note that the mapping can vary based on the context of the software under evaluation. The detailed SQ model with definitions of the QAs can be found in our Replication Package [11] under `docs/sqmodel.xlsx`.

Table 3. SQ Model

Quality Attribute	Sustainability Dimensions			
	Economic	Environmental	Social	Technical
Availability			x	x
Scalability	x			x
Time Behavior		x		x
Security	x		x	x
Interoperability	x		x	x
Portability	x		x	x
Modifiability	x			x
Reliability	x		x	x
Testability				x
Resource Utilization	x	x		x
Energy Efficiency		x		x
Analysability				x
Modularity				x
Reusability	x	x		x

DMatrix. We create a dependency matrix (DMatrix) [6] for each design option to see the inter-dimension impact of QAs. We take the QAs representing each sustainability dimension from the SQ Model. Using DMatrix, we map the QAs of technical dimension with QAs of economic (see Table 5), environmental (see Table 6) and social (see Table 7) sustainability. The impact values in DMatrix are identified based on the scenario(s) represented by the design concern. The information about these scenarios comes from the documentation as well as the architects. The DMatrix is a representation of the inter-QA and inter-dimension dependencies. The prioritized QAs act as the evaluation criteria. We create 3 DMatrices (T-Ec, T-En, T-S) per design option. For each design option, we compare the DMatrices for the same dimension pair. For example, DMatrix (T-Ec) for design option O-5.1 is only compared to DMatrix (T-Ec) for design option O-5.2, and so on. The QAs to analyze are chosen based on the set of QAs supported by all design options. Cross-dimension scores (*e.g.,* between T-Ec and T-En) can only be compared if the same list of QAs is being used in all DMatrices.

我们使用表 2 中的 QA 构建可持续发展质量 (SQ) 模型 [7]，如表 3 (Ec)、环境 (En)、社会 (S) 和技术 (T) 所示。这一映射有助于我们了解每个质量保证如何对一个或多个可持续发展维度产生影响。这对于观察跨维度可持续性权衡至关重要。值得注意的是，映射可能会根据评估软件的上下文而有所不同。带有 QA 定义的详细 SQ 模型可以在我们的复制包 [11] 的 docs/sqmodel.xlsx 中找到。

表 3. SQ 模型

质量属性	可持续发展维度 经济			
		环境的	社会的	技术的
可用性			x	x
可扩展性	x			x
时间行为		x		x
安全	x		x	x
互操作性	x		x	x
可移植性	x		x	x
可修改性	x			x
可靠性	x		x	x
可测试性				x
资源利用	x	x		x
能源效率		x		x
可分析性				x
模块化				x
可重复使用性	x	x		x

DMatrix。我们为每个设计选项创建一个依赖矩阵 (DMatrix) [6]，以查看 QA 的跨维度影响。我们从 SQ 模型中获取代表每个可持续发展维度的 QA。使用 DMatrix，我们将技术维度的 QA 与经济（见表 5）、环境（见表 6）和社会（见表 7）可持续性的 QA 进行映射。 DMatrix 中的影响值是根据设计问题所代表的场景来确定的。有关这些场景的信息来自文档和架构师。 DMatrix 是 QA 间和维度间依赖关系的表示。优先的 QA 作为评估标准。我们为每个设计选项创建 3 个 DMatrices（T-Ec、T-En、T-S）。对于每个设计选项，我们比较相同尺寸对的 DMatrices。例如，设计选项 O-5.1 的 DMatrix (T-Ec) 仅与设计选项 O-5.2 的 DMatrix (T-Ec) 进行比较，依此类推。要分析的 QA 是根据所有设计选项支持的 QA 集来选择的。仅当所有 DMatrices 中使用相同的 QA 列表时，才能比较跨维度分数（例如，T-Ec 和 T-En 之间）。

Sustainability Impact Score (SIS). Next, we prioritize one design option among available alternatives based on our evaluation criteria, *i.e.,* list of QAs. We develop a Sustainability Impact Score (see Eq. 1) to represent what is the impact of QAs within the technical dimension `T` with respect to QAs within the other sustainability dimensions `dim (Ec, En, S)`. We use the QA priority values as weights for the QA impact. We calculate the sum of the product of QA priority with the impact value for all QAs. We do not normalize the value of the score to retain the representation of the number of QAs contributing to a dimension, which becomes apparent from the relatively high magnitude of the score and vice versa (see QA number and index values in Table 5 vs Table 6). For the analysis, we compare the value of the SIS across the same dimension. The score with a relatively higher value represents higher sustainability support. Currently, we do not compare cross-dimension scores.

$$\text{Sustainability Impact Score}_{T,dim} = \sum_{\substack{i=1\\j=1}}^{n,m} (\text{Priority}_{T\_i} + \text{Priority}_{dim\_j}) \times \text{Impact}_{ij} \quad (1)$$

where n=total QAs per dimension T, m=total QAs per dimension `dim`, `dim` $\in \{$Ec, En, S$\}$, impact = $\{+1, -1, 0\}$

The SIS can be used to prioritize between design options by making a trade-off between the chosen evaluation criteria, *i.e.,* QAs. Hence, SIS can help prioritize design decisions *based on evaluation criteria*. Here, we present the evaluation of two design concerns. See the replication package [11] for all design concerns and their evaluation results.

Example 1. Here we present the detailed evaluation of design concern DC-5 (see Table 4), the design options considered and their SISs. Here, a design decision needs to be made for choosing whether independent or shared production instances need to be implemented for different institutions that collaborate and have shared data.

Table 4. Extracted Design Decisions for DC-5

Design Concern ID: DC-5				
Design Concern: Choice of the number of production instances				
Design Option ID	Design Option Description	Rationale	Supported QA(s)	Choice
O-5.1	Implement two separate Canvas production instances, allowing each institution to have autonomy over implementation settings and branding.	Both institutions seek autonomy in decision-making and distinct branding. However, certain crucial Canvas settings can only be adjusted at the account level, requiring separate instances to accommodate differing preferences.	Availability, Interoperability, Portability, Modifiability	Yes
O-5.2	Utilize a single Canvas instance shared by both institutions, compromising on implementation autonomy and branding flexibility	Requires fewer resources and reduces the overhead of policy syncronization	Resource Utilization	No

Economic Sustainability. Table 5 shows the DMatrix for the two design options of the design concern DC-5. It shows the impacts of QA support across the technical dimension (T) on QAs across the economic dimension (Ec). For design option O-5.1, resource utilization (T) has a neutral impact on modifiability (Ec) and vice versa. For O-5.2,

可持续性影响评分（SIS）。接下来，我们根据我们的评估标准（即质量保证列表）在可用替代方案中优先考虑一种设计选项。我们制定了可持续性影响评分（见公式 1）来表示技术维度 T 内的 QA 相对于其他可持续性维度 dim（Ec、En、S）内的 QA 的影响。我们使用 QA 优先级值作为 QA 影响的权重。我们计算 QA 优先级与所有 QA 影响值的乘积之和。我们不会对分数值进行归一化，以保留对某个维度有贡献的 QA 数量的表示，这从分数相对较高的幅度中变得显而易见，反之亦然（参见表 5 与表 6 中的 QA 数量和指数值） ）。为了进行分析，我们比较同一维度上的 SIS 值。数值相对较高的分数代表较高的可持续性支持。目前，我们不比较跨维度的分数。

$$\text{可持续性影响分数} = \sum_{\substack{i=1\\ j=1}}^{n,m} (\text{优先级}+\text{优先级}) \times \text{影响力} \quad (1)$$

其中 n=每个维度 T 的 QA 总数，m=每个维度 dim 的 QA 总数 , ε {}{+1, −1, 0}

SIS 可用于通过在所选评估标准（即 QA）之间进行权衡来确定设计选项的优先级。因此，SIS 可以帮助根据评估标准确定设计决策的优先顺序。在这里，我们提出对两个设计问题的评估。

有关所有设计问题及其评估结果，请参阅复制包 [11]。

示例 1. 在此，我们介绍了设计问题 DC-5 的详细评估（参见表 4）、考虑的设计选项及其 SIS。在这里，需要做出设计决策，选择是否需要为协作并共享数据的不同机构实施独立或共享的生产实例。

表 4. DC-5 的设计决策摘录

设计关注 ID：DC-5				
设计关注点：生产实例数量的选择				
设计选项 ID	设计选项说明	基本原理	支持的质量检查	选择
O-5.1	实施两个独立的 Canvas 生产实例，允许每个机构对实施设置和品牌拥有自主权。	两家机构都寻求决策自主权和独特的品牌。然而，某些关键的 Canvas 设置只能在帐户级别进行调整，需要单独的实例来适应不同的首选项。	可用性， 互操作性， 可移植性， 可修改性	Yes
O-5.2	利用两个机构共享的单个 Canvas 实例，从而牺牲实施自主权和品牌灵活性	需要更少的资源并降低策略同步的开销	资源利用	No

经济可持续性。表 5 显示了设计公司 DC-5 的两个设计选项的 DMatrix。它显示了跨技术维度 (T) 的 QA 支持对跨经济维度 (Ec) 的 QA 的影响。对于设计选项 O-5.1，资源利用率 (T) 对可修改性 (Ec) 具有中性影响，反之亦然。对于 O-5.2， resource utilization(T) has a negative impact on modifiability (Ec) and vice versa. The negative impact is also clear from the lower $SIS_{T\text{-}Ec}$ for O-5.2. Other QAs have the same impacts across both design options. It means that O-5.2 is less favorable for economic sustainability as it will be difficult to change the system per the different requirements of both institutes. As the QAs for O-5.1 hold a higher priority, the choice of this design decision remains unchanged.

Table 5. DMatrices Technical-Economic (T-Ec)

(a) O-5.1

Technical \ **Economic**		Interoperability	Portability	Modifiability	Resource Utilization
	Priority	*9*	*8*	*7*	*4*
Availability	*13*	o	o	-	o
Interoperability	*9*		+	+	+
Portability	*8*	+		+	o
Modifiability	*7*	+	+		o
Resource Utilization	*4*	o	o	o	
					$SIS_{T\text{-}Ec=89}$

(b) O-5.2

Technical \ **Economic**		Interoperability	Portability	Modifiability	Resource Utilization
	Priority	*9*	*8*	*7*	*4*
Availability	*13*	o	o	-	o
Interoperability	*9*		+	+	+
Portability	*8*	+		+	o
Modifiability	*7*	+	+		-
Resource Utilization	*4*	o	o	-	
					$SIS_{T\text{-}Ec=67}$

Environmental Sustainability. Table 6 shows the DMatrix for the two design options of the design concern DC-5 for the impact of QA support across technical dimension (T) on QAs across environmental dimension (En). For design option O-5.1, modifiability (T) has a negative impact on resource utilization (En). For design option O-5.2, modifiability (T) has a neutral impact on resource utilization (En). This is also clear from the lower $SIS_{T\text{-}En}$ for O-5.1. Other QAs have the same impacts across both design options. It means that O-5.1 is less favorable for environmental sustainability as it uses more resources. However, the decision still remains in favor of O-5.1 due to the higher priority of QAs supporting the economic dimension.

Table 6. DMatrices Technical-Environmental (T-En)

(a) O-5.1

Technical \ **Environmental**		Resource Utilization
	Priority	4
Availability	13	o
Interoperability	9	+
Portability	8	o
Modifiability	7	-
Resource Utilization	4	
		$SIS_{T\text{-}En=2}$

(b) O-5.2

Technical \ **Environmental**		Resource Utilization
	Priority	4
Availability	13	o
Interoperability	9	+
Portability	8	o
Modifiability	7	o
Resource Utilization	4	
		$SIS_{T\text{-}En=13}$

资源利用率（T）对可修改性（Ec）有负面影响，反之亦然。 O-5.2 的 SIS 较低，负面影响也很明显。其他 QA 对这两种设计选项具有相同的影响。这意味着 O-5.2 不太有利于经济可持续性，因为很难根据两个机构的不同要求来改变系统。由于 O-5.1 的 QA 具有更高的优先级，因此该设计决策的选择保持不变。

表 5. DMatrices 技术经济 (T-Ec)

(a) O-5.1

技术的 \ 经济		互操作性	可移植性	可修改性	资源利用
	优先事项	9	8	7	4
可用性	13	o	o	–	o
互操作性	9		+	+	+
可移植性	8	+		+	o
可修改性	7	+	+		o
资源利用	4	o	o	o	
SIS					

(b) O-5.2

技术的 \ 经济		互操作性	可移植性	可修改性	资源利用
	优先事项	9	8	7	4
可用性	13	o	o	–	o
互操作性	9		+	+	+
可移植性	8	+		+	o
可修改性	7	+	+		–
资源利用	4	o	o	–	
SIS					

环境可持续性。表 6 显示了设计关注点 DC-5 的两个设计选项的 DMatrix，用于跨技术维度 (T) 的 QA 支持对跨环境维度 (En) 的 QA 的影响。对于设计选项 O-5.1，可修改性 (T) 对资源利用率 (En) 具有负面影响。对于设计选项 O-5.2，可修改性 (T) 对资源利用率 (En) 具有中性影响。从 O-5.1 的较低 SIS 中也可以清楚地看出这一点。其他 QA 对这两种设计选项具有相同的影响。这意味着 O-5.1 对环境可持续性不太有利，因为它使用更多的资源。然而，由于支持经济维度的 QA 具有更高的优先级，该决定仍然支持 O-5.1。

表 6. DMatrices 技术环境 (T-En)

(a) O-5.1

技术的 \ 环境		资源利用
	优先事项	4
可用性	13	o
互操作性	9	+
可移植性	8	o
可修改性	7	
资源利用率	4	
SIS		

(b) O-5.2

技术的 \ 环境		资源利用
	优先事项	4
可用性	13	o
互操作性	9	+
可移植性	8	o
可修改性	7	o
资源利用率	4	
SIS		

Social Sustainability. Table 7 shows the DMatrix for the two design options of the DC-5 for the impact of QA support across technical dimension (T) on QAs across social dimension (S). The impacts are the same for both design decisions as well as their $SIS_{T\text{-}S}$. Hence, both of these design options have no impact on social sustainability.

Table 7. DMatrices Technical-Social (T-S)

(a) O-5.1

Technical / **Social**		Availability	Interoperability	Portability
Priority		13	9	8
Availability	13		o	o
Interoperability	9	+		+
Portability	8	o	+	
Modifiability	7	o	+	+
Resource Utilization	4	U	o	o
				$SIS_{T\text{-}S} = 87$

(b) O-5.2

Technical / **Social**		Availability	Interoperability	Portability
Priority		13	9	8
Availability	13		o	o
Interoperability	9	+		+
Portability	8	o	+	
Modifiability	7	o	+	+
Resource Utilization	4	U	o	o
				$SIS_{T\text{-}S} = 87$

Trade-Off. The results of our assessment for DC-5 shows that economic sustainability is favored over environmental sustainability by the choice of O-5.1. However, given the rationale for the decisions, this choice is still favorable. This does not mean that the chosen design decision is not sustainable, but it helps architects think other sustainability dimensions (environmental in this case) which are compromised for the chosen trade-off (in favor of economic sustainability).

Example 2. Here we present the detailed evaluation of design concern DC-6 (see Table 8), the design options considered and their SISs. This design concern refers to decision-making regarding the choice of data access and retention period for inactive users, *e.g.,* students who have graduated.

Table 8. Extracted Design Decisions for DC-6

Design Concern ID: DC-6				
Design Concern: Lifecycle and retention of course data				
Design Option ID	Design Option Description	Rationale	Supported QA(s)	Choice
O-6.1	User access period should be aligned with data retention period (7 years) to keep course history available, allowing users to retain access to Canvas even after they are no longer active within the institution.	To allow availability of data to users	Availability	Yes
O-6.2	Do not retain course history in the LMS for an extended period. Only provide access to active users.	Users may not have the option to extract materials from Canvas after they are no longer active, hence the data is using extra resources. Deleting the data may impact accreditation sources.	Security, Resource Utilization	No

社会可持续性。表 7 显示了 DC5 的两个设计选项的 DMatrix，用于跨技术维度 (T) 的 QA 支持对跨社会维度 (S) 的 QA 的影响。对于设计决策及其 SIS 的影响是相同的。

因此，这两种设计方案对社会可持续性都没有影响。

表 7. DMatrices 技术-社会 (T-S)

(a) O-5.1

技术的	社交可用性	互操作性	可移植性
优先事项	13	9	8

可用性 13 o o 互操作性 9 + + 可移植性 8 o + 可修改性 7 o + + 资源利用率 4 U o o

SIS T-S = 87

(b) O-5.2

技术的	社交可用性	互操作性	可移植性
优先事项	13	9	8

可用性 13 o o 互操作性 9 + + 可移植性 8 o + 可修改性 7 o + + 资源利用率 4 U o o

SIS T-S = 87

权衡。我们对 DC-5 的评估结果表明，选择 O-5.1 时，经济可持续性优于环境可持续性。然而，考虑到这些决定的理由，这个选择仍然是有利的。这并不意味着所选的设计决策不可持续，但它可以帮助建筑师思考其他可持续性维度（在本例中为环境），这些维度会因所选的权衡（有利于经济可持续性）而受到损害。

示例 2. 这里我们介绍了设计问题 DC-6 的详细评估（参见表 8）、考虑的设计选项及其 SIS。这种设计关注点是指关于非活跃用户（例如已毕业的学生）的数据访问和保留期限的选择的决策。

表 8. 提取的 DC-6 设计决策

设计关注 ID：DC-6				
设计关注点：课程数据的生命周期和保留				
设计选项 ID	设计选项说明	基本原理	支持的质量检查	选择
O-6.1	用户访问期限应与数据保留期限（7 年）一致，以保持课程历史记录可用，从而允许用户即使在机构内不再活跃后也可以保留对 Canvas 的访问权限。	允许用户使用数据	可用性	Yes
O-6.2	请勿在 LMS 中长时间保留课程历史记录。仅向活跃用户提供访问权限。	用户不再活跃后可能无法选择从 Canvas 中提取材料，因此数据正在使用额外的资源。删除数据可能会影响认证来源。	安全、资源利用率	No

Economic and Environmental Sustainability. Tables 9 and 10 show the DMatrix for the two design options of the design concern DC-6 for the impact of QA support across technical dimension (T) on QAs across economic dimension (Ec) and environmental dimension (En), respectively. For design option O-6.1, availability (T) has a negative impact on resource utilization (Ec, En) and vice versa. For O-6.2, availability (T) has a neutral impact on resource utilization (Ec, En). The negative impact is also clear from the lower $SIS_{T\text{-}Ec}$ for O-6.1. The same impacts are also seen across the environmental dimension with the same $SIS_{T\text{-}En}$. Other QAs have neutral impacts across both design options. It means that O-6.1 is less favorable for economic and environmental sustainability because of additional resource utilization due to long-term data storage.

Table 9. DMatrices Technical-Economic (T-Ec)

(a) O-6.1

Technical	Economic	Security	Resource Utilization
	Priority	10	4
Availability	13	o	-
Security	10		o
Resource Utilization	4	o	
$SIS_{T\text{-}Ec} = -17$			

(a) O-6.2

Technical	Economic	Security	Resource Utilization
	Priority	10	4
Availability	13	o	o
Security	10		o
Resource Utilization	4	o	
$SIS_{T\text{-}Ec} = 0$			

Social Sustainability. Availability (T) and Security (T) have a positive impact on each other (S) across the social dimension (see Table 11) while Resource Utilization (T) has a negative impact on availability (S). Relatively, O-6.1 has a higher $SIS_{T\text{-}S}$ showing support for social dimension.

Trade-Off. The results of our assessment for DC-6 show that social sustainability is favored over economic and environmental sustainability by the choice of O-6.1. In the currently chosen option, social sustainability is favored as the availability of data is given more importance based on the institute's policy decisions (also reflected by the high priority of Availability QA).

Table 10. DMatrices Technical-Environmental (T-En)

(a) O-6.1

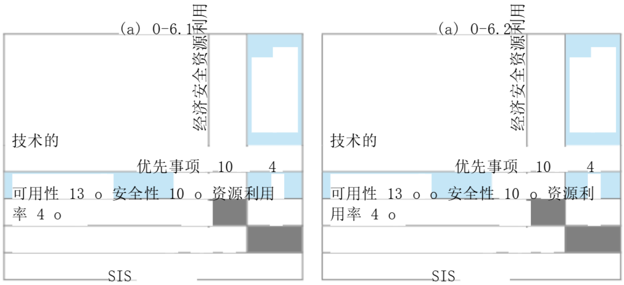
Technical	Environmental	Resource Utilization
	Priority	4
Availability	13	-
Security	10	o
Resource Utilization	4	
$SIS_{T\text{-}En} = -17$		

(b) O-6.2

Technical	Environmental	Resource Utilization
	Priority	4
Availability	13	o
Security	10	o
Resource Utilization	4	
$SIS_{T\text{-}En} = 0$		

经济和环境的可持续性。表 9 和表 10 显示了设计关注点 DC-6 的两个设计选项的 DMatrix，分别表示跨技术维度 (T) 的 QA 支持对跨经济维度 (Ec) 和环境维度 (En) 的 QA 的影响。对于设计选项 0-6.1，可用性 (T) 对资源利用率（Ec、En）有负面影响，反之亦然。对于 0-6.2，可用性 (T) 对资源利用率 (Ec、En) 具有中性影响。 0-6.1 的 SIS 较低，负面影响也很明显。使用相同的 SIS，在环境维度上也可以看到相同的影响。其他 QA 对这两种设计选项具有中性影响。这意味着 0-6.1 对经济和环境可持续性不太有利，因为长期数据存储会导致额外的资源利用。

表 9. DMatrices 技术经济 (T-Ec)



社会可持续性。可用性 (T) 和安全性 (T) 在整个社会维度上对彼此 (S) 产生积极影响（见表 11），而资源利用率 (T) 对可用性 (S) 产生负面影响。相对而言，0-6.1 的 SIS 较高，显示出对社会维度的支持。

权衡。我们对 DC-6 的评估结果表明，选择 0-6.1 时，社会可持续性优于经济和环境可持续性。在当前选择的选项中，社会可持续性受到青睐，因为根据研究所的政策决策，数据的可用性更加重要（也反映在可用性质量保证的高度优先级上）。

表 10. DMatrices 技术环境 (T-En)

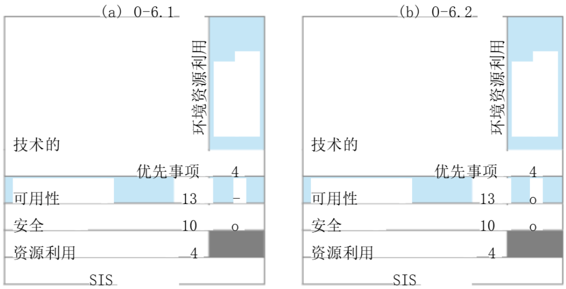


Table 11. DMatrices Technical-Social (T-S)

(a) O-6.1

Technical \ Social		Availability	Security
Priority		13	10
Availability	13		+
Security	10	+	
Resource Utilization	4	o	o
SIS_{T-S} = 46			

(b) O-6.1

Technical \ Social		Availability	Security
Priority		13	10
Availability	13		o
Security	10	o	
Resource Utilization	4	o	o
SIS_{T-S} = -17			

X. Improve and Take Action. Table 12 displays the SIS for each design option and highlights the inter-dimension sustainability trade-offs made for each design concern. Among all design concern options, O-1.1 stands out for its lack of sustainability support, prompting a recommendation to change the decision to O-1.2.

While O-5.1 prioritizes the economic dimension, it makes a trade-off across the social dimension. We do not recommend any changes here as the economic dimension is represented by high-priority QAs.

Although O-9.1 offers strong sustainability support across two dimensions (Ec and S), O-9.2 provides comparatively balanced sustainability support. The choice of O-9.1 is better as it supports maximum sustainability dimensions however, it could be argued that O-9.2 could provide a balanced sustainability support as all dimensions are relatively equally supported. In such a case, the use of expert knowledge becomes imperative for decision-making.

Table 12. Chosen design options and sustainability trade-offs

Design Concern ID	Design Option ID	Choice	SIS_{T-Ec}	SIS_{T-En}	SIS_{T-S}	Is sustainability addressed?
DC-1	O-1.1	Yes	0	0	0	No
	O-1.2	No	41	78	49	
DC-2	O-2.1	Yes	11	0	0	Yes
	O-2.2	Yes	0	0	0	
DC-3	O-3.1	Yes	43	0	43	Yes
	O-3.2	Yes	0	0	0	
DC-4	O-4.1	Yes	34	0	55	Yes
	O-4.2	Yes	31	0	51	
DC-5	O-5.1	Yes	89	2	87	Partially
	O-5.2	Yes	67	13	87	
DC-6	O-6.1	Yes	-17	-17	46	Partially
	O-6.2	Yes	0	0	-17	
DC-7	O-7.1	Yes	66	0	81	Yes
	O-7.2	Yes	0	0	0	
DC-8	O-8.1	Yes	0	-15	0	Yes
	O-8.2	Yes	0	-15	0	
DC-9	O-9.1	Yes	68	0	51	Partially
	O-9.2	Yes	32	38	32	

☐ = higher SIS, ☐ = lower SIS

表 11. DMatrices 技术-社会 (T-S)

(a) O-6.1

技术的 \ 社交	优先事项	可用性	安全
优先事项		13	10
可用性	13		+
安全	10	+	
资源利用	4	o	o
SIS			

(b) O-6.1

技术的 \ 社交	优先事项	可用性	安全
优先事项		13	10
可用性	13		o
安全	10	o	
资源利用	4	o	o
SIS			

X. 改进并采取行动。 表 12 显示了每个设计选项的 SIS，并强调了针对每个设计问题进行的跨维度可持续性权衡。在所有设计关注选项中，O-1.1 因其缺乏可持续性支持而脱颖而出，促使建议将决定更改为 O-1.2。

虽然 O-5.1 优先考虑经济维度，但它在社会维度上进行了权衡。我们不建议在此进行任何更改，因为经济维度由高优先级 QA 代表。

尽管O-9.1在两个维度（Ec和S）上提供了强大的可持续发展支持，但O-9.2提供了相对平衡的可持续发展支持。选择 O-9.1 更好，因为它支持最大的可持续性维度，但是，可以说 O-9.2 可以提供平衡的可持续性支持，因为所有维度都得到相对平等的支持。在这种情况下，利用专业知识进行决策就变得势在必行。

表 12. 选择的设计方案和可持续性权衡

设计关注点 ID	设计选项 ID	选择	SIS	SIS	SIS	可持续性是否得到解决？
DC-1	O-1.1	Yes	0	0	0	No
	O-1.2	No	41	78	49	
DC-2	O-2.1	Yes	11	0	0	Yes
	O-2.2	Yes	0	0	0	
DC-3	O-3.1	Yes	43	0	43	Yes
	O-3.2	Yes	0	0	0	
DC-4	O-4.1	Yes	34	0	55	Yes
	O-4.2	Yes	31	0	51	
DC-5	O-5.1	Yes	89	2	87	部分
	O-5.2	Yes	67	13	87	
DC-6	O-6.1	Yes	-17	-17	46	部分
	O-6.2	Yes	0	0	-17	
DC-7	O-7.1	Yes	66	0	81	Yes
	O-7.2	Yes	0	0	0	
DC-8	O-8.1	Yes	0	-15	0	Yes
	O-8.2	Yes	0	-15	0	
DC-9	O-9.1	Yes	68	0	51	部分
	O-9.2	Yes	32	38	32	

= 更高的 SIS， = 较低的 SIS

We conducted a reflective session with an architect to discuss our results, the implications of SIS, and to gather feedback. We suggested revisiting the design decisions in cases with a negative impact on sustainability. The architect found the SIS useful for objective decision-making. They highlighted that different stakeholders may prioritize QAs in a different order and suggested that the prioritization should give more weight to the choice of those stakeholders most affected by a design concern. Our analysis helped the experts view the design decisions in the context of their sustainability support through different QAs.

XI. Presentation of Results. Detailed results are presented as part of the replication package [11]. The architects confirmed that the provided templates are useful and they plan to use them in their future decision-making process. We plan to provide a formal report to present to the technical team of the project for taking appropriate action.

6 Discussion

In this section, we present insights from our results, the challenges faced in the SA assessment, and the future direction of our research.

Insights. Our assessment helped the experts see two types of trade-offs: (i) Inter-QA trade-offs (*i.e.,* trade-offs between two different QAs, *e.g.,* maintainability and resource utilization) through the D-Matrix in terms of inter-QA dependencies, and (ii) Inter-dimension trade-offs (*i.e.,* trade-offs between two sustainability dimensions *e.g.,* economic and environmental) through the SIS. Our study helps the evaluators visualize the interdependencies for such trade-offs for informed decision-making. The evaluators agreed that the SQ Model helped them visualize the sustainability dimensions per QA which they were not so sure about before the assessment.

The SIS aids decision-making by quantifying the sustainability support across dimensions, hence enabling evaluators to consider alternative design options for better trade-offs. Experts find this approach clear and easy to use, with SIS quantification enhancing understanding of decision impacts and enabling informed decision-making.

Looking at the design decisions and assessing them for sustainability based on experience-based technique becomes harder when the number of QAs and decisions increase [9]. Our approach helps address this complexity issue thanks to the SIS, which streamlines the assessment process by providing a consolidated evaluation of sustainability dimensions and highlighting trade-offs that may not be immediately evident. By using a blend of experience-based and quantitative technique, we support evaluators in the decision-making process.

Challenges. Specifically for our case study, the assessment posed certain challenges. Navigating the case study's SA and documentation was difficult. With steps VII and VIII of our method, we uncovered missing information in the architecture documentation. This encompassed both documented and undocumented design decisions, including design options, rationales, and relevant QAs. This recovered information is crucial for mapping the right QAs with design options and facilitating informed decision-making.

我们与一位架构师进行了反思会议，讨论我们的结果、SIS 的影响并收集反馈。我们建议在对可持续性产生负面影响的情况下重新审视设计决策。架构师发现 SIS 对于客观决策非常有用。他们强调，不同的利益相关者可能会以不同的顺序对质量保证进行优先排序，并建议优先级应该更加重视受设计问题影响最大的利益相关者的选择。我们的分析帮助专家通过不同的质量保证在可持续发展支持的背景下查看设计决策。

十一.结果介绍。 详细结果作为复制包的一部分提供[11]。架构师确认所提供的模板很有用，他们计划在未来的决策过程中使用它们。我们计划提供一份正式报告，提交给项目的技术团队，以便采取适当的行动。

6 讨论

在本节中，我们将介绍我们的结果、SA 评估中面临的挑战以及我们研究的未来方向。

见解。我们的评估帮助专家们看到了两种类型的权衡：（i）通过 D 矩阵在相互之间进行 QA 权衡（即两个不同 QA 之间的权衡，例如可维护性和资源利用率）。 QA 依赖性，以及 (ii) 通过 SIS 进行维度间权衡（即两个可持续性维度（例如经济和环境）之间的权衡）。我们的研究帮助评估者可视化这种权衡的相互依赖性，以做出明智的决策。评估人员一致认为，SQ 模型帮助他们可视化每个 QA 的可持续性维度，而他们在评估之前对此不太确定。

SIS 通过量化跨维度的可持续性支持来帮助决策，从而使评估人员能够考虑替代设计选项以实现更好的权衡。专家们发现这种方法清晰且易于使用，SIS 量化可以增强对决策影响的理解并实现明智的决策。

当质量保证和决策数量增加时，基于经验技术来审视设计决策并评估其可持续性变得更加困难 [9]。我们的方法有助于解决这一复杂性问题，这要归功于 SIS，它通过提供可持续性维度的综合评估并强调可能不会立即显现的权衡来简化评估流程。通过结合使用基于经验和定量技术，我们在决策过程中为评估人员提供支持。

挑战。特别是对于我们的案例研究，评估提出了某些挑战。浏览案例研究的 SA 和文档非常困难。通过我们方法的第七步和第八步，我们发现了架构文档中缺失的信息。这包括记录和未记录的设计决策，包括设计选项、基本原理和相关的质量保证。这些恢复的信息对于将正确的质量保证与设计选项进行映射并促进明智的决策至关重要。

The experts noted that some decisions are made without having a choice, *i.e.,* there are no alternatives available. For such cases, the design decisions are typically not documented. However, it is possible that such decisions could inadvertently impact a QA not considered initially. Hence, missing the inter-QA or inter-dimension trade-offs.

In our SA assessment, we do not prioritize the sustainability dimensions. However, there might be an implicit priority associated with them based on the sustainability mapping in the SQ Model. Table 3 shows that most of the chosen QAs inherently support economic and technical sustainability while a few support environmental and social sustainability. Hence, sustainability dimensions mapped to low-priority QAs or less number of QAs might get overlooked. For informed decision-making, a re-prioritization might be appropriate after making the SQ Model. Such re-prioritization is supported inherently in the blueprint due to the oscillating nature of Step VI–Prioritization. We observe that a higher value of the SIS is due to either the high priority of the chosen QAs or a relatively higher number of the total QAs for design option(s).

Future Directions. We only use 3 values of impacts (+1, −1, 0) in the DMatrix. However, the positive impact of one QA may be stronger than the other, making the representation of this relative strength apparent. It would be valuable to quantify a comparable impact score across different dimensions (say S and Ec) to see by what margin a dimension is favored over another during the trade-off. We aim to calculate SIS across other combinations of dimensions, *i.e.,* Ec-En, Ec-S etc.. and refine it to improve its support for a more objective SA assessment, and evaluate the effectiveness of this approach through systematic feedback from the evaluators, *e.g.,* through questionnaire survey.

7 Threats to Validity

We use the classification from Wohlin *et al.* [23] to identify threats to validity and present our mitigation actions.

Construct Validity. The possibility of internal bias of the experts was mitigated by cross-examining their decisions and rationale and questioning them. Further, the study design and result of each evaluation phase were cross-checked by the second author. We do not normalize the SIS values to avoid the loss of meaningful variation due to the number of QAs considered and their respective priority.

Internal Validity. The choice of design concerns for analysis was based on the availability of data hence the choice is not biased by any selection criteria. The design decisions were evaluated after being translated from Dutch to English, hence creating a risk of loss of contextual information or correctness. We mitigated this issue by the review of translated documents by the architects who are native Dutch speakers and have knowledge of the SA. The results of the evaluation show that the chosen design options and QA priorities match, hence confirming the evaluation results. The quantification was done by the research team and then we went back to confirm the results from the experts, who agreed. We also provide a replication package for the study.

External Validity. The case study focuses on a specific software system in one organization. While the SA assessment method is reusable and not tied to a particular SA, the evaluation results are specific to the studied SA.

专家们指出，有些决定是在没有选择的情况下做出的，即没有其他选择。对于这种情况，通常不会记录设计决策。然而，此类决定可能会无意中影响最初未考虑的质量保证。因此，缺少质量保证间或维度间的权衡。

在我们的 SA 评估中，我们没有优先考虑可持续性维度。然而，根据 SQ 模型中的可持续性映射，可能存在与它们相关的隐式优先级。表 3 显示，大多数选定的 QA 本质上支持经济和技术可持续性，而少数则支持环境和社会可持续性。因此，映射到低优先级 QA 或较少数量的 QA 的可持续性维度可能会被忽视。为了做出明智的决策，在制定 SQ 模型后重新确定优先级可能是合适的。由于步骤 VI（优先级划分）的波动性质，蓝图中固有地支持这种重新确定优先级。我们观察到，SIS 的较高值是由于所选 QA 的高优先级或设计选项的总 QA 数量相对较多。

未来的方向。我们在 DMatrix 中仅使用 3 个影响值 (+1, -1, 0)。然而，一个 QA 的积极影响可能比另一个更强，从而使这种相对强度的表现变得明显。量化不同维度（例如 S 和 Ec）的可比影响分数，以了解在权衡过程中某个维度比另一个维度更受青睐的幅度是很有价值的。我们的目标是跨其他维度组合（即 Ec-En、Ec-S 等）计算 SIS，并对其进行改进，以提高其对更客观 SA 评估的支持，并通过评估者的系统反馈来评估该方法的有效性，例如通过问卷调查。

7 有效性的威胁

我们使用 Wohlin 等人的分类。[23] 识别有效性威胁并提出我们的缓解措施。

构造有效性。通过交叉检查专家的决定和理由并提出质疑，减少了专家内部偏见的可能性。此外，每个评估阶段的研究设计和结果均由第二作者交叉检查。我们不对 SIS 值进行标准化，以避免由于考虑的 QA 数量及其各自的优先级而导致有意义的变化的损失。

内部有效性。用于分析的设计关注点的选择是基于数据的可用性，因此该选择不会受到任何选择标准的影响。设计决策从荷兰语翻译成英语后进行评估，因此存在丢失上下文信息或正确性的风险。我们通过以荷兰语为母语并且了解 SA 的建筑师对翻译文件的审查来缓解这个问题。评估结果表明，所选的设计方案与质量保证优先级相匹配，从而确认了评估结果。研究小组做了量化，然后我们回去向专家确认结果，专家也同意了。我们还为该研究提供了复制包。

外部有效性。该案例研究重点关注一个组织中的特定软件系统。虽然 SA 评估方法是可重复使用的并且不依赖于特定 SA，但评估结果特定于所研究的 SA。

8 Conclusion and Future Work

In this study, we present, (i) an instantiation of an SA assessment method for sustainability with a blend of experience-based and quantitative techniques, (ii) a Sustainability Impact Score for informed decision-making, and (iii) application of our SA assessment method on a real case. Our results provide insights to the architects on possible sustainability trade-offs that they must consider to make design decisions. The SIS score shows whether a design choice is made based on prioritizing a certain dimension over another or balancing the trade-offs across all dimensions. The quantitative assessment simplifies the process of complex decision-making for the architects. The assessment results help architects in observing the inter-QA and inter-dimension trade-offs of their choices.

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Data Availability Statement. The data for the study has been made available as a replication package online [11].

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8　结论和未来的工作

在本研究中，我们提出了（i）结合基于经验和定量技术的可持续发展 SA 评估方法的实例，（ii）用于明智决策的可持续发展影响评分，以及（iii）我们的基于真实案例的SA评估方法。我们的研究结果为建筑师提供了关于可能的可持续性权衡的见解，他们在做出设计决策时必须考虑这些权衡。 SIS 分数显示设计选择是基于优先考虑某个维度而不是另一个维度还是平衡所有维度的权衡。定量评估简化了建筑师复杂的决策过程。评估结果帮助架构师观察他们的选择的内部质量检查和内部维度权衡。

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数据可用性声明。该研究的数据已作为复制包在线提供[11]。

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