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DEXiWare: a software development framework for building cooperative decision support systems

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ABSTRACT

The development of decision support systems (DSS) for agriculture increasingly relies on complex decision models, yet transforming such models into operational, user-friendly software remains challenging. DEXiWare is a software framework designed to support the development of web-based, cooperative DSS based on decision models built with the DEX (Decision EXpert) method. The framework provides a standardized workflow for operationalizing decision models, including automated model import, data handling, assessment, and scenario analysis, within a reusable backend–frontend architecture. DEXiWare integrates backend services, a web-based user interface, and a decision engine supporting top-down (goal-seeking) and bottom-up (what-if) scenario exploration. The framework is evaluated through its application in multiple agricultural DSS and through usability testing with stakeholders, demonstrating its applicability for translating qualitative decision models into operational decision support tools for sustainability assessment in agricultural production systems.

Metadata

Nr	Code metadata description	*Metadata*
C1	Current code version	*V1.0.0.*
C2	Permanent link to code/repository used for this code version	https://github.com/EcoEnvAI/DEXiWare
C3	Permanent link to reproducible capsule	*DOI:* 10.5281/zenodo.18030971
C4	Legal code license	*GNU General Public License (GPL)*
C5	Code versioning system used	*git*
C6	Software code languages, tools and services used	*Javascript, Node.js, Angular, PostgreSQL, Java, DEX, Docker*
C7	Compilation requirements, operating environments and dependencies	*/*
C8	If available, link to developer documentation/manual	*API documentation (accessible locally):* http://localhost:8080/api-docs/
C9	Support email for questions	dexiware@ijs.si

1. Motivation and significance

A decision support system (DSS) is an interactive computer-based system intended to help decision makers identify and solve problems, complete decision process tasks, and make reliable decisions [1]. The rapid development of DSS for agriculture is reflected in the growing number of tools available [2–5]. This widespread use of DSS underlines the increasing reliance on decision support methods to optimize agricultural practices and improve sustainable crop production.

However, the rapid growth of available DSS has unexpectedly raised doubts among their users about the reliability and trustworthiness of their results. The results of a survey of DSS users conducted in 12 different workshops across Europe [6] show that the most prevalent barriers to DSS adoption are: i) lack of trust in DSS, ii) the belief that users need additional training in IT and computer science, and iii) lack of market information about DSS. These barriers are partly related to usability, understood here as the extent to which a system can be used by specified users to achieve specified goals effectively, efficiently, and with satisfaction in a given context of use, following the ISO 9241-11 definition as discussed in [7].

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To address recurring challenges in translating qualitative decision models into operational DSS, we present DEXiWare, a generic software development framework for building web-based DSS based on the DEX method. While domain-specific modelling remains central to DSS development, DEXiWare addresses the complementary challenge of operationalizing decision models by providing a standardized software workflow that supports model import, data handling, assessment, and scenario analysis within a reusable architecture. The objective of this paper is to describe the design of DEXiWare and to validate its applicability through its use in two agricultural DSS, illustrating how the process of moving from models to operational DSS can be streamlined. The framework is evaluated through its application in multiple DSS, usability testing with stakeholders, and assessment of its support for systematic scenario analysis.

The development of DEXiWare is informed by our extensive experience with predecessor systems, notably EVADIF [8] and the LANDMARK project's Soil Navigator [9,10]. Soil Navigator with its models, in particular, has gained significant traction in the research community, being utilized to study how management practices impact soil functions at field level. This tool has catalyzed new research on soil functions, including studies in Europe [11–13], ongoing research in China [14], and helped produce new research hypothesis [15]. Its widespread use by researchers and recognition by policymakers have contributed to its influence on the EU soil policies [16]. Following Soil Navigator, DEXiWare has been adopted across several Horizon Europe projects, reflecting its expanding role in supporting research and policy efforts aimed at promoting sustainable agriculture [17–20].

While earlier systems such as EVADIF and Soil Navigator demonstrated the scientific value of DEX-based decision support, they were primarily developed as project-specific solutions. DEXiWare builds on this experience by introducing a standardized workflow for developing DSS, including a reusable backend architecture, a consistent user interaction pattern, and integrated support for cooperative work. A key contribution of DEXiWare is that it makes systematic exploration of decision models feasible in practice by embedding both top-down (goal-seeking) and bottom-up (what-if) scenario analysis directly into the software framework. Without such integration, these analyses would require extensive manual execution and would therefore be impractical for real-world use.

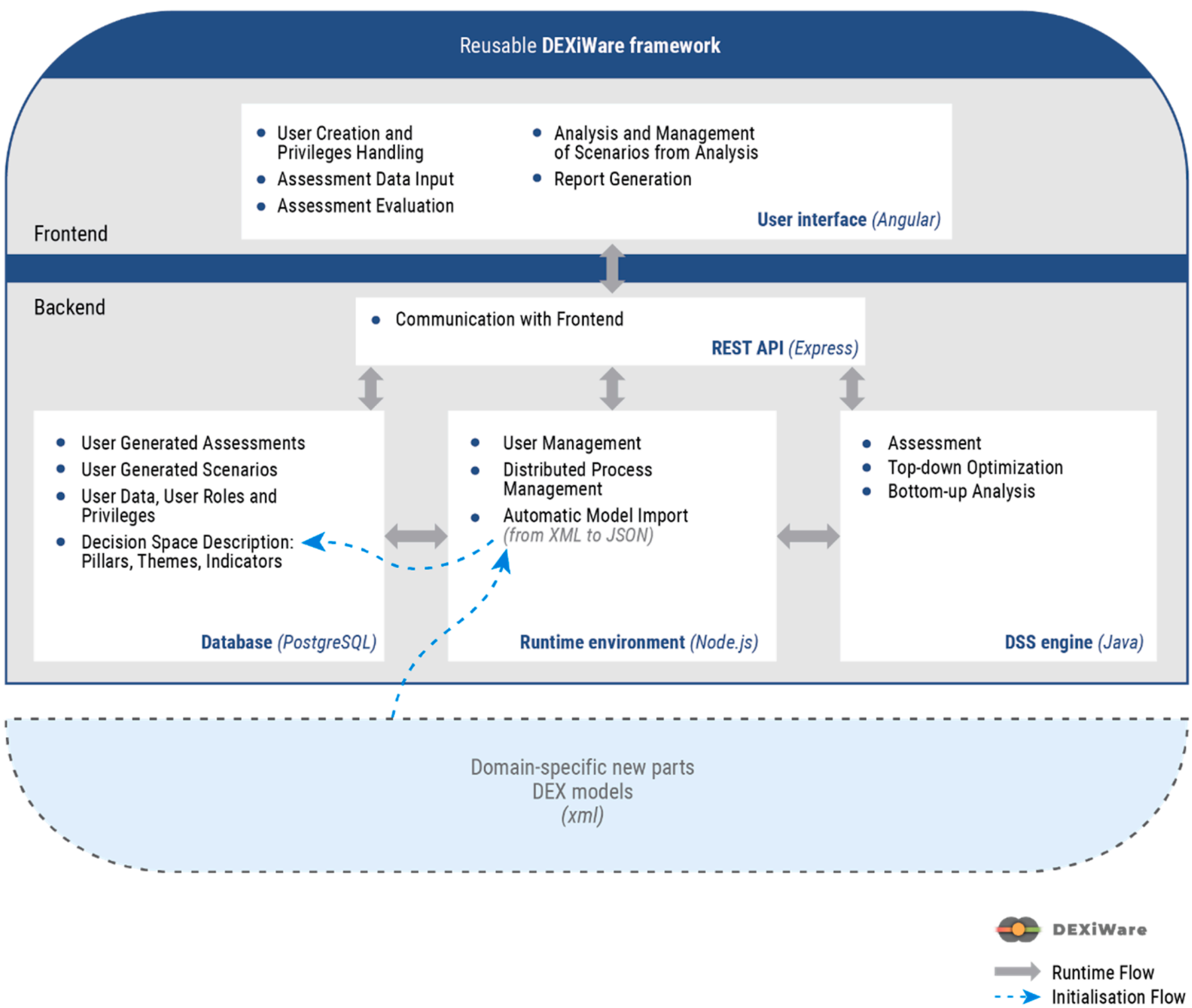

Fig. 1. Block diagram of a DSS built with DEXiWare. Blue arrows (initialization flow) show the flow of information when the system is automatically created from the domain specific models. Grey arrows (runtime flow) show the communication between the main components during operation. Communication between frontend and backend components is based on standard HTTP/REST interfaces, database access is handled via standard database drivers, and interaction between the runtime environment and the DSS engine is managed via Node-based Java processes.

2. Software description

By abstracting domain-independent components, DEXiWare provides ready-to-use solutions for backend services, frontend user interfaces, user management, data storage, and specific, but domain independent DSS features like top-down and bottom-up scenario exploration.

2.1. DEXiWare architecture

The DEXiWare framework consists of two main components: frontend (FE) and backend (BE), which communicate via a Representational State Transfer Application Programming Interface (REST API) (Fig. 1). Together with domain-specific models, they form a complete DSS that can be deployed as a web application. The BE comprises three main blocks: database, runtime engine, and DSS engine. The runtime engine handles communication with the database, user authentication, and interaction with the DSS engine. The DSS engine performs assessments as well as top-down and bottom-up scenario exploration based on user input. The database is implemented using PostgreSQL, with data access handled in the runtime environment using the Sequelize ORM, and stores decision models' structure and user-generated content. The FE, developed as a single-page application in Angular, enables user interaction. It was designed with usability Nielsen's 10 usability heuristics in mind [21] and enables user registration, data entry, evaluation, and scenario analysis supporting cooperation among multiple users.

2.2. Domain-specific models

DEXiWare builds DSS based on qualitative multi-attribute decision models developed with the DEX method [22]. DEX is supported by the free DEXi software, which helps decision-makers to develop decision models and use them to evaluate and analyze decision problems [22]. As the use of DEX method is widespread in agriculture [9,23–27], DEXiWare builds on this foundation and provides the missing parts that generate a DSS based on DEX decision models developed with DEXi tool.

2.3. DEXiWare framework

Runtime Environment (BE): The runtime environment ensures an efficient flow of data between the FE and the BE by designing and running operational tasks that break down complex data management into smaller, manageable modules. It imports decision models from DEXi's XML format into JSON, automatically creates the database structure, interacts with the DSS engine and serves the FE via a REST API. It is implemented in Node.js with the Express web application framework.

Database (BE): The database schema accommodates heterogeneous decision models with hierarchical structures. The user input data are called indicators. Each indicator belongs to a hierarchical data structure consisting of different levels of aggregations of qualitative attributes into, e.g. pillars, themes, nodes, pillars (as in the Pathfinder DSS). Further structuring into sub-hierarchical levels is possible with the help of a recursive foreign-key. The structure is determined by the DEX models. User-generated content, such as indicator values and assessments, are stored separately from the structure itself.

DSS Engine (BE): The DSS engine communicates with DEX models to assess decision outcomes and perform scenario analyses. It supports top-down analyses (determination of actions to achieve the desired outcomes) and bottom-up analysis (evaluation of outcomes based on specific input conditions). The DSS engine is implemented in Java and is managed via Node-based distributed processes.

User Interface (FE): The FE is a web application accessible through a browser. It supports complex decision-making processes and guides users through features such as user permission management (Fig. 2a), data entry (Fig. 2b), assessment (Fig. 2c), and top-down and bottom-up scenario exploration (Fig. 2d). The interface provides detailed descriptions of indicators, checks for missing data, and presents results

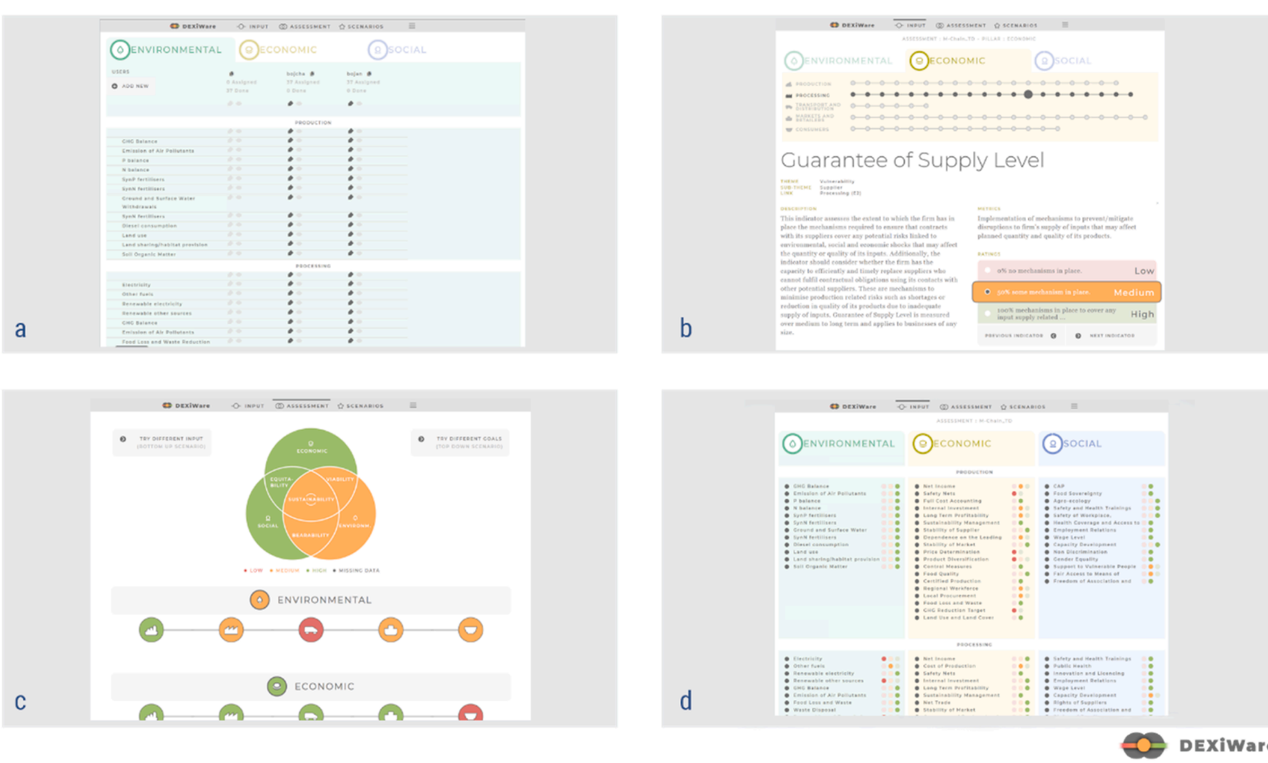

Fig. 2. Elements of the DEXiWare framework: (a) user permission management, (b) data entry for a single indicator with clear navigation of the decision problem represented with pillars, nodes, and (sub) themes, (c) visualization of the results of the current assessment, and (d) interface for what-if or bottom-up analyses. Screenshots from the Pathfinder DSS (a, b, c) and the Resource Amplifier DSS (d) which were developed with DEXiWare.

graphically. Users can analyze alternatives and create exportable PDF reports.

3. Illustrative examples - software evaluation

This section evaluates DEXiWare as a software framework. The evaluation is based on three complementary aspects: (i) its application in multiple DSS, (ii) the ability of the software to support systematic analysis of decision models, including top-down and bottom-up scenario exploration, and (iii) usability evaluation with end users.

3.1. Application of DEXiWare in the development of DSS

DEXiWare was validated through its application in the development of two DSS in agriculture: the Pathfinder (PF) [28] and the Resource Amplifier (RA) [29]. This section outlines the common development steps using the DEXiWare methodology.

The first step is to use the DEXi tool to develop domain-specific DEX decision models, which are then used to structure the database of DEXiWare-based DSS with all the information for the user including indicator names, ratings and descriptions. The RA DSS models assess and rank tomato production systems based on resource-use efficiency, environmental impacts, and socio-economic factors [30]. These models were developed using knowledge from data mining and domain experts, hierarchically structured, and validated using real-world data. On the other hand, PF assesses the sustainability of legume-based supply chains by assessing environmental, economic, and social pillars and their integration [31]. The models use a tiered structure to assess individual links within the agri-food chain and integrate these assessments into an overall sustainability evaluation.

The next step is importing domain-specific decision models into DEXiWare through the runtime environment module (initialization flow in Fig. 1), which is executed automatically when the system is started using Docker Compose and can be customized to accommodate project-specific requirements. Decision models developed in DEX are exported in XML format and automatically processed by DEXiWare to generate the corresponding database structure, including indicators, hierarchical relationships, and user-oriented descriptive metadata. This process ensures consistency between the decision model and the operational DSS and enables the user interface to be constructed directly from the imported model structure. As a result, domain experts can focus on modelling in the DEX environment, while DEXiWare handles the transformation of decision models into a fully functional, web-based DSS.

Finally, the user interface can be customized for branding and user experience. An end-user license agreement template is also provided.

3.2. Validation of decision model behavior in deployed DSS

An important aspect of the evaluation of DEXiWare is its ability to support systematic analysis of decision models beyond single-point assessments. First, consistency between the original DEX decision models and the DSS generated with DEXiWare was verified by comparing assessment results produced directly by the models with those obtained through the deployed DSS, confirming that model behavior is preserved after deployment.

In addition, DEXiWare enables structured exploration of decision models through integrated bottom-up (what-if) and top-down (goal-seeking) scenario exploration. These analyses allow users to evaluate the effects of alternative input configurations and to identify combinations of indicator values that lead to desired outcomes. While such analyses are in principle possible using decision models alone, performing them manually would be time-consuming and impractical for complex models. By embedding these capabilities directly in the DSS, DEXiWare makes systematic scenario exploration feasible in practice without requiring users to interact directly with the underlying models.

3.3. Usability evaluation

Usability was selected as an evaluation focus because DEXiWare-based DSS are intended for use by domain experts and stakeholders who are not necessarily trained in information technology. Ensuring that such users can effectively interact with the system is therefore a prerequisite for practical adoption.

Quantitative usability evaluation was conducted for the Pathfinder DSS using the System Usability Scale (SUS) questionnaire [32], a standardized instrument widely used for assessing perceived usability with relatively small samples [33]. The questionnaire was administered to 14 stakeholders after hands-on use of the system. The resulting mean SUS score was 71.96, corresponding to “good usability” according to established interpretation guidelines [34].

In addition, formative usability feedback was collected for other DEXiWare-based tools, most notably the Market Avenue Generator (MAG) [35]. Usability was assessed qualitatively through repeated pilot use during development and through hands-on workshops conducted on multiple occasions, involving more than 60 participants in total. During these sessions, users interacted with the system and provided structured and open feedback, which was documented and used to iteratively improve the user interface and workflow of DEXiWare.

4. Impact

DEXiWare enables research questions that require systematic exploration of qualitative decision models to be addressed in practice. In particular, it supports research that involves analyzing alternative scenarios, trade-offs, and target-oriented outcomes using DEX models, including top-down (goal-seeking) and bottom-up (what-if) scenario exploration. These types of analyses are commonly needed and often impractical to perform manually for models of realistic size and complexity.

By providing a standardized software framework for operationalizing DEX-based decision models, DEXiWare improves the pursuit of existing research questions by allowing decision models developed in scientific studies to be deployed as interactive, multi-user DSS. This facilitates their use beyond the modelling phase, for example in comparative case studies, stakeholder engagement, and iterative assessment across different contexts. The applicability of this approach is demonstrated through multiple DSS developed with DEXiWare, including PF [28] and RA [29], which have been used in published and citable research outputs. With DEXiWare, instead of relying on static model evaluations or expert-only tools, users can interactively enter data, explore scenarios, store results, and collaborate with other users through a web-based interface. Usability evaluations and qualitative feedback from stakeholders indicate that such systems can be effectively used by non-technical users.

The framework has been developed through and adopted in a range of European research and innovation projects, including LANDMARK, TRUE, TOMRES, RADIANT, BENCHMARKS, and LegumES [36–42] demonstrating uptake beyond a single project or use case. These projects cover different domains within agriculture and environmental management, indicating that the framework is applicable across diverse decision contexts.

While DEXiWare is primarily used in research and advisory settings, its structured and reusable architecture has also supported the development of tools that are explored in pre-commercial and innovation-oriented contexts, such as the MAG. These applications suggest potential for future commercial use, although systematic evaluation of commercial impact is beyond the scope of this paper.

5. Conclusions

This paper presented DEXiWare, a software development framework for building web-based DSS. The main contributions are:

- a standardized software workflow for operationalizing DEX-based decision models, including automated model import, data handling, assessment, and scenario analysis;
- a modular web-based architecture that supports multi-user DSS deployment while allowing domain experts to focus on decision modelling;
- integrated support for top-down (goal-seeking) and bottom-up (what-if) scenario analysis, enabling systematic exploration of decision models;
- validation through application in multiple agricultural DSS, demonstrating applicability across different decision contexts;
- usability evaluation indicating that DSS developed with DEXiWare can be used effectively by non-technical stakeholders.

These results demonstrate that DEXiWare facilitates the translation of qualitative decision models into operational DSS. Future work will focus on extending multilingual support, further usability evaluation, and integration of additional modelling approaches.

Availability: DEXiWare is freely accessible through its current implementations. The Resource Amplifier is available at http://resourceamplifier.ijs.si, the Pathfinder at http://pathfinder.ijs.si, while the Market Avenue Generator at https://ecoenvai.ijs.si/radiant/bm-dss. The source code is available at https://github.com/EcoEnvAI/DEXiWare. Information about the DEXiWare framework is available at http://dexiware.ijs.si. DEX-related software is available at https://dex.ijs.si/.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used OpenAI's large language model gpt5 to improve the style and conciseness of the paper to meet the guidelines for the "Original software publication" article type. After using this tool/service, the authors have reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Bojan Blažica: Writing – original draft, Supervision, Software, Conceptualization. **Vladimir Kuzmanovski:** Writing – original draft, Software, Conceptualization. **Marko Bohanec:** Writing – review & editing, Software, Investigation. **Tanja Dergan:** Validation, Investigation, Data curation. **Aneta Ivanovska:** Methodology, Funding acquisition, Conceptualization. **Jurij Marinko:** Validation, Investigation. **Robert Modic:** Software, Conceptualization. **Matevž Ogrinc:** Software, Conceptualization. **Marko Debeljak:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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