POLITECNICO DI TORINO

Master's Degree in Data Science and Engineering

Master's Degree Thesis

Data Science and Search Engines for Green Technologies and Sustainable Industries

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Summary

This thesis presents the development of an innovative digital platform designed to facilitate industrial symbiosis (IS) and promote circular economy (CE) practices in waste management. The research addresses the critical challenges of resource scarcity and environmental sustainability by leveraging modern web development frameworks and advanced search capabilities to connect waste producers with potential users, streamline waste-to-resource conversion processes, and provide valuable consultancy services.

The platform's architecture combines a robust backend powered by NestJS and MongoDB with a user-friendly frontend built on Vue.js. This technical foundation supports key features including:

1. User registration and profile management
2. Advanced waste product listing and search functionality
3. End-of-Waste (EoW) conversion services
4. Integration of specialized consultancy services

The research demonstrates the potential of digital technologies in overcoming traditional barriers to IS implementation, such as information gaps, geographical limitations, and regulatory complexities. While the platform shows promising results in facilitating waste exchange and promoting sustainable practices, the study also identifies areas for future enhancement, including the integration of machine learning for predictive analytics, blockchain for improved traceability, and expanded global reach through multilingual support.

Our work contributes to the growing body of knowledge on technology-enabled circular economy solutions and offers a practical tool for industries seeking to transition towards more sustainable resource management practices.

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Acronyms

IS

Industrial Symbiosis

CE

Circular Economy

EoW

End-of-Waste

WRC

Waste-to-Resource Conversion

Chapter 1

Introduction

1.1 Background

The concept of industrial symbiosis (IS) has gained significant traction in recent years as industries and governments seek more sustainable practices. IS is a key strategy within the broader framework of circular economy (CE), aiming to create a more sustainable and efficient industrial ecosystem. IS involves the exchange of materials, energy, water, and by-products between traditionally separate industries. This approach is inspired by natural ecosystems, where waste from one organism becomes a resource for another. In the industrial context, the waste or by-products from one company become valuable inputs for another, creating a network of resource exchange that reduces overall waste and improves resource efficiency.

The origins of IS can be traced back to Kalundborg, Denmark, where a well-developed network of resource exchanges between different industries has been in place since the 1960s. This pioneering example demonstrated how collaboration and geographic proximity could lead to significant environmental and economic benefits.

In recent years, the advancement of information and communication technologies (ICT) has opened up new possibilities for expanding IS beyond geographical constraints. Online platforms and tools are now playing a crucial role in facilitating IS by connecting potential partners across wider regions and providing data-driven insights for optimal resource matching.

1.2 Problem Statement

Despite the potential benefits of IS, several challenges hinder its widespread adoption:

- Information gap: Many companies struggle to identify suitable partners for waste exchange or to navigate the complexities of waste-to-resource conversion (WRC). There is often a lack of data about available materials, waste generated, and potential uses for these resources.
- Geographical limitations: Traditional IS models often rely on physical proximity between industries, limiting the potential for synergies across wider regions.
- Technological barriers: The lack of efficient tools to match waste producers with potential buyers hampers the widespread adoption of IS practices.
- Data complexity: The vast amount of data involved in tracking and categorizing various waste streams presents a significant challenge in matching supply with demand effectively.
- Regulatory hurdles: Varying environmental regulations across different regions can complicate the implementation of IS strategies.
- Trust and cooperation: There can be reluctance among companies to establish synergistic relations due to concerns about confidentiality, reliability, or quality of exchanged resources.
- Knowledge gap: Many stakeholders lack a comprehensive understanding of IS concepts and their potential benefits.

These challenges collectively contribute to missed opportunities for resource efficiency, continued waste generation, and slower progress towards CE goals.

1.3 Objectives

The primary objectives of this research are multifaceted and interconnected, all aimed at facilitating and enhancing IS through digital innovation.

- Firstly, this study aims to develop a comprehensive digital platform that facilitates waste exchange between companies. This involves designing and implementing a user-friendly interface for companies to list, search, and transact waste products, as well as creating a robust database structure to store and manage information on resources, wastes, and conversion processes.

- Secondly, the thesis seeks to implement advanced search algorithms that efficiently match waste producers with potential buyers. This objective involves developing and integrating intelligent matching algorithms based on material properties, quantities, and geographical locations.
- Thirdly, we intend to provide a knowledge base for WRC processes. This includes compiling and organizing information on various WRC technologies and best practices, as well as implementing a system for continuous updating of this knowledge base.
- Lastly, our project aims to incorporate end-of-waste (EoW) conversion services and consultancy options within the platform. This involves integrating features to connect users with EoW conversion service providers and developing a module for expert consultancy services to help users optimize their IS strategies.

1.4 Scope and Limitations

This thesis encompasses the full-stack development of the waste exchange platform, including both backend and frontend components. The scope of the study is comprehensive and covers several key areas of development and implementation. The project includes the design and implementation of the database structure. This involves the development of the API which is a crucial aspect of the project. This involves creating RESTful API endpoints for data input, retrieval, and management, as well as implementing secure authentication and authorization mechanisms. The thesis also covers the implementation of the user interface and search functionality. This involves designing an intuitive web-based interface for users to interact with the platform and developing advanced search and filtering capabilities to help users find relevant matches. The implementation of matching algorithms is a core component of the platform. This involves developing and integrating intelligent matching algorithms based on material properties, quantities, and geographical locations.

However, it is important to note several limitations. The platform will be developed as a prototype and may not include all the features necessary for immediate commercial deployment. The legal and regulatory aspects of waste management will be considered in the design, but may require further development to ensure full compliance in different jurisdictions. The initial focus will be on specific waste streams limited at geographic level since the project starts as a POC with a few partners.

Despite these limitations, a robust online platform aims to demonstrate this potential in fostering sustainable industrial practices, while data science is poised to further enhance these efforts in the future, paving the way for more efficient resource utilization and waste reduction across industries.

1.5 Outline of Thesis

This thesis is structured into seven chapters, each addressing key aspects of the development and implementation of a digital platform for IS.

- Chapter 2 presents a comprehensive literature review, exploring the concepts of CE and IS, WRC technologies, the role of big data in sustainable industries, and the application of search engines in industrial contexts.
- Chapter 3 delves into the platform's features and functionality. It covers user registration and profiles, waste product listing, search capabilities, EoW conversion services, and consultancy services integration.
- Chapter 4 details the methodology employed. It describes the system architecture, backend development (including database design, search functionalities, API development), and frontend development with Vue.js.
- Chapter 5 presents a theoretical evaluation of the platform's design and potential impact. It includes an analysis of the key components and their implications for IS practices, along with a discussion of limitations and areas requiring future validation.
- Chapter 6 explores potential areas for future work, including the integration of machine learning for predictive analytics, blockchain for traceability, enhanced user experience features, global expansion possibilities, and advanced data analytics capabilities.
- Chapter 7 concludes the thesis by summarizing the key contributions of the study in the context of digital innovation for industrial symbiosis and circular economy practices.

Chapter 2

Literature Review

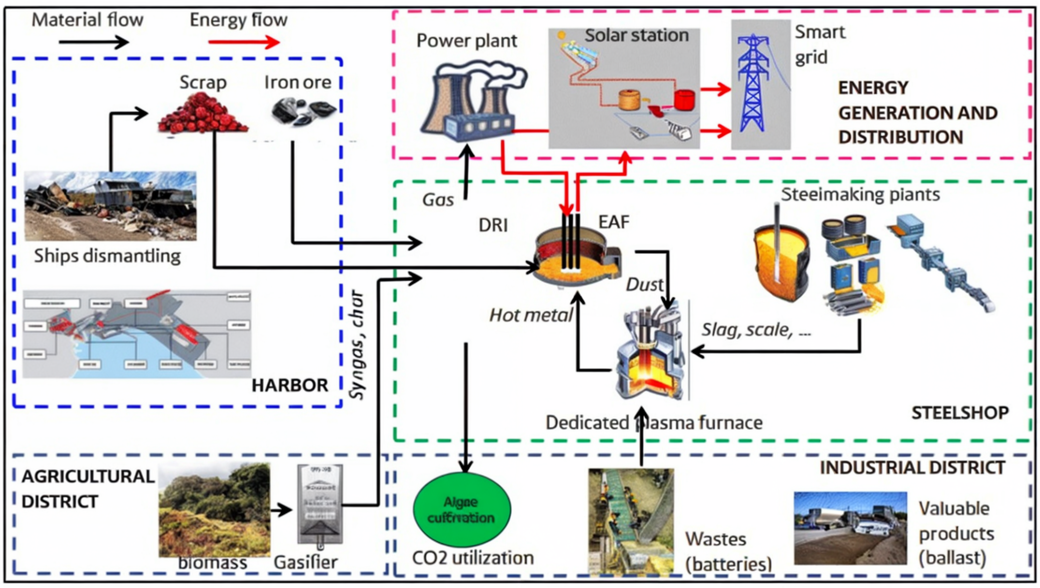

Figure 2.1: Conceptual design of steel industry-based industrial symbiosis. Adapted from [1].

2.1 Circular Economy and Industrial Symbiosis

The concepts of CE and IS have gained significant attention in recent years as strategies to address resource scarcity and environmental challenges [2]. The CE aims to transform the traditional linear "take-make-dispose" economic model into a more sustainable closed-loop system where resources are used, recovered, and regenerated more efficiently [European Commission, 2015]. IS, a key enabler of the CE, focuses on creating networks of industrial exchanges where waste or by-products from one industry become valuable resources for another [3]. This approach not only reduces waste and resource consumption but also offers economic benefits through cost savings and new revenue streams [4]. The concept of IS originated with the Kalundborg Eco-industrial Park in Denmark, which has been implementing symbiotic exchanges between co-located industries for over 60 years [3]. This pioneering example demonstrated how companies from diverse sectors such as power generation, oil refining, pharmaceuticals, and construction materials could create a network of material and energy exchanges, significantly reducing their environmental footprint while improving economic performance [3].

Since then, IS initiatives have expanded globally, with notable examples in Nordic countries like Sweden and Finland, as well as emerging networks in countries like China and Greece [2]. These initiatives vary in scale, from eco-industrial parks to regional and national networks, and have shown promising results in terms of resource efficiency and economic benefits [2].

However, developing and scaling up IS networks remains challenging due to several barriers [5]:

- **Information gaps:** Lack of comprehensive information about potential synergies, available waste streams, and conversion technologies often hinders the identification of symbiosis opportunities.
- **Limited scope:** Many existing approaches focus on simple one-to-one exchanges rather than more complex multi-party networks, potentially missing out on more significant symbiosis opportunities.
- **Trust and cooperation:** Companies may be reluctant to share information about their waste streams or to rely on other companies' by-products as inputs, due to concerns about confidentiality, reliability, or quality.
- **Regulatory barriers:** Existing regulations may not always support or may even hinder the reuse of waste materials, creating legal obstacles to symbiosis initiatives.
- **Technical and economic feasibility:** Not all theoretically possible exchanges are technically or economically viable, requiring careful assessment of conversion processes, transportation costs, and market demands.

To overcome these barriers and unlock the full potential of IS, researchers and practitioners have emphasized the need for improved information systems and tools. These solutions aim to facilitate IS by connecting potential partners, providing knowledge on WRC options, and supporting decision-making processes [6].

2.2 Waste-to-Resource Conversion

At the heart of IS is the concept of WRC, where materials traditionally considered as waste are transformed into valuable inputs for other processes. This section explores the diverse range of conversion pathways and technologies that enable such transformations.

The literature highlights numerous examples of innovative WRC across various industries. In the realm of agricultural waste valorization, Low et al. [7] discuss how apple peels, a common by-product of food processing, can be converted into high-value compounds through different processes. These include the extraction of polyphenols for use in plastics and pharmaceuticals, recovery of anthocyanins as visual markers in live cell imaging, and isolation of flavonoids for dietary supplements.

Cellulose production from waste sources is another area of focus. The same study by Low et al. [7] highlights how cellulose, a crucial material for paper, textiles, and building materials, can be produced from rice straw through processes like iodine-catalyzed chemical modification or steam explosion combined with mechanical separation. Paper waste can also be repurposed by extracting fibrous pulps during the recycling process.

Electronic waste recycling has gained attention due to the growing concern in our tech-driven economy. Silva et al. [5] discuss the recovery of valuable metals and other materials from electronic waste, highlighting the potential for resource reclamation in this sector.

The Kalundborg symbiosis network provides classic examples of industrial by-product utilization, such as using excess steam from a power plant for heating in nearby refineries or pharmaceutical plants [3]. This showcases how waste energy from one process can become a valuable input for another.

Recent technological advancements have expanded the possibilities for WRC. Advanced separation techniques have improved the efficient recovery of valuable components from complex waste streams. Biotechnology, utilizing microorganisms and enzymes, enables the conversion of organic wastes into high-value products like biofuels, biochemicals, and bioplastics. Nanotechnology offers new possibilities for resource recovery and waste treatment at the molecular level, opening up innovative approaches to WRC [5].

Despite the technical feasibility of many WRC processes, several challenges persist. Economic viability remains a key concern, as the cost of conversion processes and transportation must be balanced against the value of recovered resources. Ensuring consistent quality of recovered materials to meet industrial standards can be challenging, especially with heterogeneous waste streams. Regulatory compliance presents another hurdle, as companies must navigate complex waste management regulations and obtain necessary permits for waste processing and reuse. Market development also poses challenges, including creating stable markets for recovered materials and overcoming potential stigma associated with "waste-derived" products [5].

The literature emphasizes that while technical solutions exist for recycling or converting most types of waste into useful resources, the key challenge lies in making these solutions economically viable and practically implementable at scale [5]. This underlines the need for comprehensive information systems and decision support tools to help identify and evaluate the most promising waste-to-resource opportunities [6]. By addressing these challenges and leveraging technological advancements, WRC has the potential to play a crucial role in advancing IS and promoting a more promoting CE [5].

2.3 Big Data in Sustainable Industries

The advent of big data analytics and advanced information systems has opened up new possibilities for enabling large-scale IS and CE initiatives [8]. This section explores how big data approaches are being applied to overcome information barriers and optimize resource exchanges.

Key applications of big data in the context of IS include [8]:

- **Comprehensive databases:** Creation of large-scale databases that capture detailed information on waste streams, material flows, and conversion technologies across different industries and regions. These databases serve as the foundation for identifying potential symbiosis opportunities.
- **Network detection algorithms:** Development of sophisticated algorithms that can analyze complex data sets to detect potential symbiosis networks and optimize resource exchanges. These algorithms can identify non-obvious connections and multi-party exchanges that might be missed by manual analysis.
- **Online platforms and marketplaces:** Creation of digital platforms that connect waste producers with potential users, facilitating transactions and information exchange. These platforms can operate at local, regional, or even global scales [5].

- **Predictive analytics:** Use of historical data and machine learning techniques to forecast waste generation, resource availability, and market demands, enabling more proactive planning of symbiosis initiatives.

- **Environmental impact assessment:** Integration of life cycle assessment (LCA) data to evaluate the environmental benefits of proposed symbiosis exchanges, helping to prioritize the most impactful initiatives.

While big data approaches offer significant potential for advancing IS, several challenges remain [8]:

- **Data quality and standardization:** Ensuring the accuracy, completeness, and comparability of data from diverse sources remains a significant challenge.

- **Privacy and security concerns:** Companies may be hesitant to share detailed information about their processes and waste streams, necessitating robust data protection measures.

- **Real-time data processing:** Developing systems capable of processing and analyzing data streams in real-time to enable more dynamic and responsive symbiosis networks.

- **Interdisciplinary collaboration:** Bridging the gap between data scientists, environmental experts, and industry practitioners to develop truly effective solutions.

2.4 Search Engines for Industrial Applications

To make IS knowledge more accessible and actionable, researchers have proposed specialized search engines and knowledge management systems [6]. These tools aim to overcome the limitations of traditional databases and manual facilitation approaches by enabling more dynamic and intelligent querying of IS opportunities [6]. Several researchers have leveraged graph database technologies to model and query complex IS networks:

- **Waste-to-Resource Matching Engine:** Low et al. [7] developed a database engine for waste-to-resource matching using Neo4j, a graph database platform. Their approach models resources, processes, and companies as nodes in a graph, with edges representing input-output relationships. This structure allows for efficient querying of conversion pathways and potential symbiosis partners.

- **IS Knowledge Graph:** Chatzidimitriou et al. [9] created a knowledge graph to represent IS data, enabling more sophisticated querying and reasoning.

These graph-based approaches offer several advantages over traditional relational databases, including more flexible data modeling, improved performance for relationship-heavy queries, and better support for discovering non-obvious connections [9]. While these search engines and platforms offer significant potential for facilitating IS, several challenges and areas for improvement remain [6]:

- **Data collection and updating:** Maintaining up-to-date and comprehensive databases on waste streams, conversion technologies, and company capabilities remains a challenge. Future systems may need to incorporate more automated data collection methods, potentially leveraging Internet of Things (IoT) sensors and real-time data feeds.

- **Quantification of benefits:** Current systems often lack robust capabilities for quantifying the economic and environmental benefits of proposed symbiosis exchanges. Integration with life cycle assessment (LCA) tools and economic modeling could enhance decision support capabilities.

- **User adoption and engagement:** Encouraging widespread adoption by industry remains a challenge. Future platforms may need to focus on improving user experience, demonstrating clear value propositions, and potentially integrating with existing enterprise resource planning (ERP) systems.

- **Handling of confidential information:** Developing mechanisms to allow companies to share sufficient information for matchmaking while protecting sensitive data.

- **Integration of regulatory information:** Incorporating up-to-date regulatory data to help users navigate compliance issues related to waste reuse and transportation.

- **Artificial Intelligence and Machine Learning:** Exploring the potential of AI and ML techniques to improve matching algorithms, predict future waste generation and resource needs, and optimize symbiosis networks.

Chapter 3

Platform Features and Functionality

This chapter outlines the core features and functionalities of the platform, designed to streamline waste management processes and enhance user experience. Each feature plays a critical role in supporting the transition to a circular economy by connecting waste producers with users, offering consultancy services, and facilitating End-of-Waste (EoW) procedures.

3.1 User Registration and Profiles

The platform provides a seamless user registration process, allowing organizations to register either as companies or consultants. The registration system is designed to facilitate waste management tracking and resource optimization through site-specific management.

3.1.1 Registration Process

Users register by providing essential organizational details, including company name, business registration number, and primary contact information. Upon email verification, users select their role as either a company or consultant, which determines their platform capabilities and interface.

3.1.2 User Roles

Companies: Organizations that manage waste streams and transformations. They may have multiple industrial sites, where for each site, they can define waste outputs (materials leaving the site), waste transformation processes, and desired end-of-waste (EoW) inputs.

Consultants: Professionals or organizations providing waste management expertise who provide recommendations and services.

3.1.3 Profile Management

Each user maintains a profile dashboard tailored to their role:

- **Company Profiles:**
  - Manage company information and contacts
  - Create and oversee multiple sites
  - Track and update site-specific waste entities
  - Search, match and start conversations with other companies
- **Consultant Profiles:**
  - Showcase expertise and services
  - Manage conversations

3.2 Waste Product Listing

The waste product listing and search functionality form the core of the platform, enabling companies to list available waste materials and/or search for materials relevant to their needs.

3.2.1 Waste Listing

Companies can easily create detailed waste product listings, specifying key information such as:

- Type of waste material (e.g., plastic, metal, organic waste)
- Quantity available
- Location
- Pricing

Listings are displayed in a structured format, allowing users to quickly assess the materials on offer.

3.3 End-of-Waste (EoW) Conversion Services

The End-of-Waste (EoW) conversion service is one of the platform's most critical features, supporting the transformation of waste materials into reusable products that meet specific regulatory standards.

3.3.1 EoW input Request

Companies can request EoW conversion services through the platform. This request includes detailed information about the waste material, such as type, condition, and intended reuse. The platform matches these requests with certified facilities or consultants who specialize in EoW processes.

3.3.2 Search Functionality with Elasticsearch

The platform leverages Elasticsearch to provide a powerful and efficient search system, enabling users to find waste materials based on various filters and criteria:

Core Search Features

- **Full-text Search**:
  - Intelligent matching of material descriptions and specifications
  - Support for partial word matches and fuzzy searching
- **Advanced Filtering**:
  - Waste type categorization
  - Price range filtering
  - Material properties (recyclable, non-recyclable, hazardous)
  - Quantity-based filtering
  - Availability dates

This advanced search functionality, powered by Elasticsearch, ensures that users can quickly and effectively find relevant materials, facilitating efficient waste material matching and promoting circular economy practices.

3.4 Consultancy Services Integration

The platform integrates consultancy services, helping users navigate complex regulations, optimize waste management practices, and transition towards sustainable business models.

3.4.1 Consultant-Client Interaction

Users can search for consultants based on expertise, location, and service offerings. Once a suitable consultant is found, users can request services directly through the platform. The platform provides tools for communication, streamlining the consultancy process.

Chapter 4

Methodology

4.1 System Architecture

Our solution utilizes a state-of-the-art web application stack, specifically designed to address the complexities of waste management and circular economy processes. The system is built with a robust architecture to ensure scalability, reliability, and flexibility in handling diverse user needs and large data volumes.

Table 4.1: System Architecture and Technologies Overview

Component	**Technology/Framework**	**Purpose**
Backend	NestJS	Server-side application framework
Database	MongoDB	NoSQL database for flexible data storage
Search Engine	Elasticsearch	Full-text search and advanced querying capabilities
Frontend	Vue.js	User interface development

4.2 Backend Development

4.2.1 Backend Architecture

The backend is powered by NestJS, an advanced Node.js framework. NestJS forms the core of the system, enabling the creation of a scalable and reliable server-side application. Its architecture is well-suited for handling complex business logic while providing a stable API layer. For data storage, MongoDB is used. As a NoSQL database, MongoDB offers flexibility compared to traditional relational databases. Its document-oriented structure allows for easy adjustments and scalability, making it ideal for managing the evolving nature of waste management data. The schema-less nature of MongoDB enables agile development and adaptation to changing requirements in the circular economy domain.

4.2.2 Framework and Technologies

The backend is developed using NestJS, a highly efficient and scalable framework. Following the MVC (Model-View-Controller) pattern, NestJS ensures the application is modular and easy to maintain. The use of TypeScript throughout the backend provides strong typing, enhancing code reliability and maintainability.

4.2.3 Database Design

The database architecture employs MongoDB, a NoSQL database system, chosen for its flexibility and scalability in handling complex waste management data structures. MongoDB's document-oriented storage model is particularly well-suited for managing diverse data types and relationships, enabling efficient handling of unstructured or semi-structured data commonly encountered in waste management applications. While these capabilities may exceed current requirements, adopting a NoSQL database from the outset ensures future scalability and simplifies potential system expansion. As shown in Figure 4.1, the schema is organized around key collections that represent the core entities of the system. Details about the structure and schemas are provided in section B.2.

Data Validation and Integrity

To maintain data quality and consistency, we implement:

- **Schema Validation**: MongoDB schema validation rules enforce document structure and field types at the database level.
- **Application-Level Validation**: Additional validation logic in the application layer handles complex business rules and cross-collection relationships.
- **Referential Integrity**: A simple middleware which ensures that when one document references another (like a Site referring to a WasteInput), the referenced document actually exists. This maintains data consistency despite MongoDB's lack of built-in foreign key constraints.

4.2.4 Search Engine Implementation

The platform leverages Elasticsearch to provide powerful search capabilities essential for efficient waste material discovery and matching. Elasticsearch serves as a

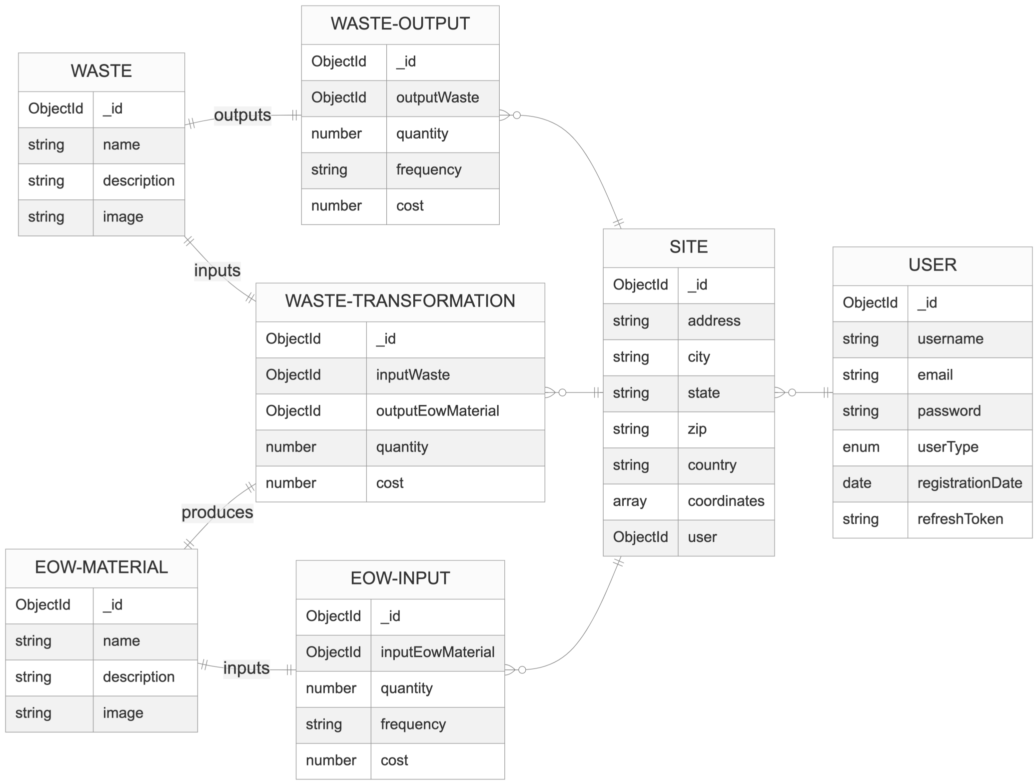

Figure 4.1: Entity-Relationship Diagram of the Database

complementary system to MongoDB, specifically optimized for search operations.

Elasticsearch Architecture

The Elasticsearch implementation is structured to support:

- Full-text search across waste material descriptions
- Geospatial queries for location-based matching
- Real-time indexing of new listings
- Advanced filtering and aggregation capabilities

Search Features

The search implementation includes:

- **Multi-field Search**: Enables searching across multiple attributes simultaneously
- **Geospatial Search**: Allows radius-based searching for nearby materials
- **Faceted Navigation**: Provides dynamic filtering options based on material properties
- **Fuzzy Matching**: Handles typos and variations in search terms
- **Relevance Scoring**: Custom scoring rules based on multiple factors including:
  - Material match quality
  - Geographic proximity
  - Quantity availability

4.3 API Development

The platform implements a RESTful API architecture, structured around domain-specific controllers that implement waste management operations, material transformation tracking, and asynchronous user communications. Each controller provides a set of endpoints that handle specific operations within their domain, following REST principles for resource manipulation.

4.3.1 API Operations and Database Interactions

Authentication System

The authentication system implements several key operations that modify database state:

Login Process

- Validates credentials against the User collection
- Generates new JWT access and refresh tokens
- Updates the User document with new refresh token data

Registration Flow

- Validates email uniqueness in User collection
- Creates new User document with secure password hash
- Generates initial Site document for company registrations
- Establishes default profile settings and permissions

Waste Management Operations

- **Waste Output Registration**
  This process involves multiple database operations:
  - Creates new WasteOutput document with specified parameters
  - Updates parent Site document with output reference
  - Indexes output details in Elasticsearch for searching
  - Updates search indices for WasteOutput matching
- **Transformation Process Management**
  Handles the registration and updating of waste transformation capabilities:
  - Creates WasteTransformation documents
  - Updates Site transformation capabilities
  - Establishes links between input waste and output materials
  - Updates search indices for transformation matching
- **EoW Input Requirements**
  Manages end-of-waste material needs:
  - Creates EOWInput documents for material requirements
  - Updates Site document with input specifications
  - Updates search indices

Search and Matching System

The search system performs complex operations across multiple collections:

- Queries Elasticsearch indices for material matches
- Applies multi-criteria filtering:

  - Material specifications
  - Geographical constraints
  - Quantity requirements
  - Economic parameters

- Generates relevance scores for results

Communication System

Handles all aspects of user communication:

- Creates and updates Message documents
- Maintains conversation threads
- Manages message status and delivery

Site Management Operations

Manages industrial site information:

- Creates and updates Site documents
- Manages geographical data
- Updates capability specifications
- Maintains site relationships

More details about endpoints and their arguments are provided in section B.1.

4.3.2 Security Implementation

To protect sensitive data and ensure secure operations, the platform implements a comprehensive set of security measures across multiple layers. These layers cover authentication, authorization, platform security, and data transmission.

- **Authentication and Authorization**

  The platform employs a secure approach for user authentication and access control.

  - **JWT-Based Token System**
    - A **dual-token** system with **refresh token rotation** ensures secure user sessions.

    * Short-lived access tokens and longer-lived refresh tokens are used to minimize exposure to token theft.
    * **Refresh token rotation** prevents repeated use of the same refresh token, adding a layer of protection.

  - **Secure Password Hashing with Bcrypt**
    * Passwords are hashed using **bcrypt** with adaptive salt rounds to mitigate brute-force attacks.
    * The hashing process includes unique salt generation for each password, ensuring enhanced security.
    * **Salt rounds** are tuned to balance security with performance.

  - **Role-Based Access Control (RBAC)**
    * Role-specific permissions are defined for companies, consultants, and administrative users.
    * Access control is enforced at the **API level**, limiting data access based on user roles.

- **Platform Security**

  The platform's infrastructure incorporates preventative measures against injection attacks and ensures secure data transmission.

  - **Input Validation and Sanitization**
    * All incoming data is validated using **class-validator** to ensure type safety and data integrity.
    * Input data is sanitized to prevent injection attacks and other forms of data manipulation.

This layered security architecture provides robust protection for user data and platform integrity, combining modern authentication mechanisms, secure password handling, and comprehensive input validation.

4.4 Frontend Development

4.4.1 Key UI Features

The user interface is designed to enhance user interaction and facilitate waste management processes. These features are implemented across various pages and components of the platform, with each component interacting with the backend through a REST API for dynamic content and data operations.

User Dashboard

As shown in Figure 4.2, the user dashboard serves as the central hub for managing accounts and accessing key functionalities. It communicates with the backend API to retrieve user-specific data such as account information, waste listings, and site management details. Key elements of the dashboard include:

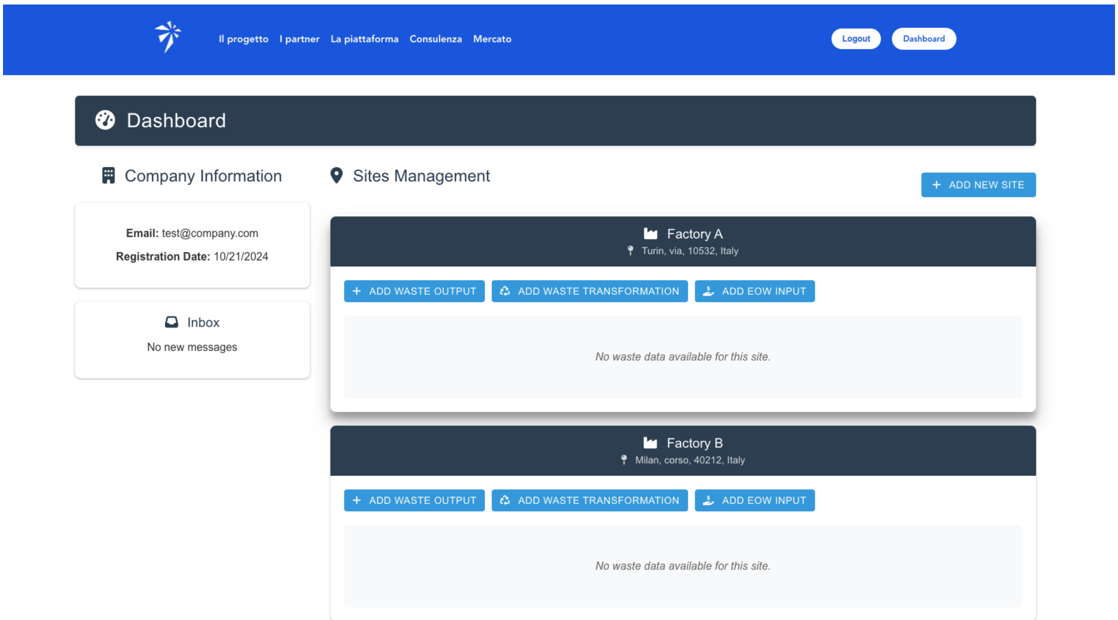

Figure 4.2: User Dashboard Interface

- **Company Information** section for managing organization details.
- **Sites Management** section, with options to add and manage new sites.
- Ability to add **waste output, waste transformation,** and **EoW input** for each site, using the API for record creation and updates.
- **Inbox feature** for messaging and notifications, using the Messaging API for asynchronous communication.

Main Landing Page

The main landing page (Figure 4.3) serves as the entry point for users. Key features include:

- **Hero banner** explains the platform's purpose and value.

- **Quick access buttons** for core functionalities (e.g., "Marketplace", "Consultants"), each navigating to the corresponding pages and triggering API calls to retrieve relevant data.
- **Trust-building elements** such as partner logos or testimonials.

EoW Marketplace

As presented in Figure 4.4, the EoW marketplace is a central feature of the platform, enabling users to browse, buy, or exchange waste materials. Key aspects include:

- **Grid-based layout** for browsing waste products.
- **Product cards** displaying material type, quantity, and origin.
- **Search and filter functionality** for efficient product discovery, using Elasticsearch API endpoints to refine search results based on user preferences.

Consultancy Services

The consultancy services page (Figure 4.5) allows users to access professional guidance for waste management activities. Key features include:

- **Overview of services** available for consultancy.
- **Service descriptions** providing details on each offering.
- **Call-to-action buttons** for users to engage and communicate with consultants.

4.4.2 Frontend Architecture and Stack

The frontend architecture is implemented using Vue.js, a JavaScript framework chosen for its component-based structure, which supports responsive design and modularity.

Component Interaction with REST APIs

Components are structured to facilitate seamless interactions with the backend.For instance:

- **User Dashboard** components interact with user and site management endpoints, retrieving or updating site-specific waste data.
- **Marketplace Search** components leverage Elasticsearch APIs for waste material search, enabling full-text and filtered searches.

- **Messaging and Notifications** components use the Messaging API to send and receive messages.

Navigation

The frontend architecture organizes key sections (Landing Page, User Dashboard, Marketplace, Consultancy Services) within a structured navigation system.

Vue.js components communicate using an event-driven model, promoting inter-component communication and data handling across sections. This model supports scalability, allowing the addition of new functionalities with minimal impact on the existing structure.

4.5 Design Choices and Implementation Challenges

The development of the platform involved several critical architectural decisions, starting with the selection of NestJS as our backend framework. This choice was primarily driven by NestJS's modular architecture and native TypeScript support, which enabled better code organization and type safety across the platform's complex waste management operations. The framework's modularity proved particularly valuable in maintaining clear separation between different features like waste management, user authentication, and messaging systems.

Our decision to use MongoDB as the primary database, while powerful, presented unique challenges in managing data relationships and validation rules without traditional SQL constraints. The schema-less nature of MongoDB required careful balance between flexibility and data consistency, particularly when handling growing datasets in the Site collection and optimizing complex queries across multiple collections. To address these challenges, we implemented careful indexing strategies and structured our data models to anticipate scaling concerns.

The integration of Elasticsearch for search functionality and the implementation of our REST API infrastructure brought their own set of challenges. Maintaining data synchronization between MongoDB and Elasticsearch required robust mechanisms for handling updates, deletions, and index rebuilding, while also optimizing for geospatial queries. On the API front, we focused on implementing secure token-based authentication with role-based access control, while also addressing practical concerns like efficient pagination, complex search parameters, and media content handling. These components all required careful consideration to ensure both security and performance at scale.

4.5.1 Current Technical Limitations and Future Considerations

Several limitations in the current implementation present opportunities for future improvement:

1. **Real-time Updates:** The current architecture doesn't support real-time updates for waste listings and matches. While WebSocket support could be added through NestJS's built-in Gateway, this would require significant architectural changes.

2. **Integration Capabilities:**

   - Limited support for external system integration
   - Lack of standardized API for third-party extensions
   - Need for more robust error handling and recovery mechanisms

3. **Monitoring and Analytics:**

   - Limited built-in monitoring capabilities
   - Need for more comprehensive logging and debugging tools

Although these challenges and limitations exist, the modular architecture of the platform allows for incremental improvements and extensions to address these limitations over time.

Figure 4.3: Main Landing Page

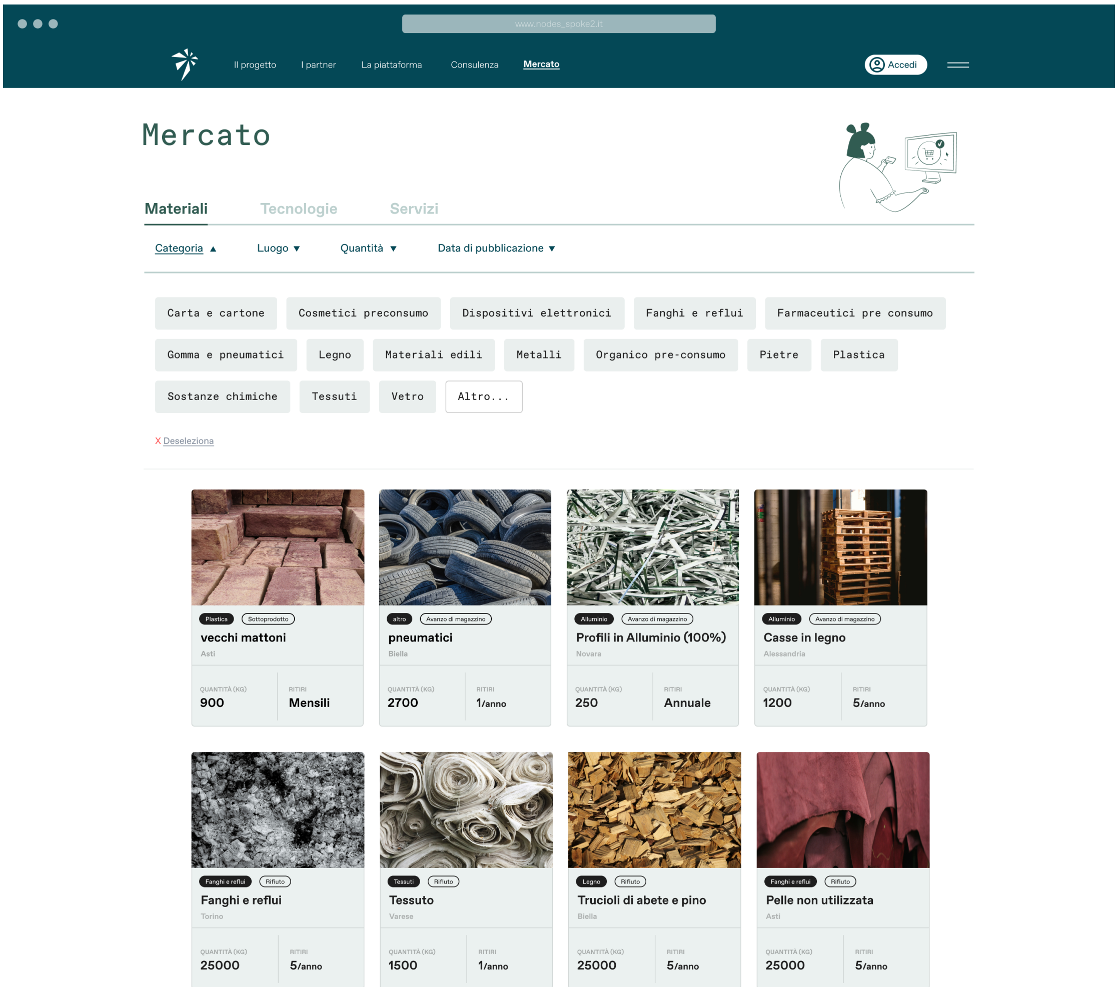

Figure 4.4: EoW Marketplace Interface

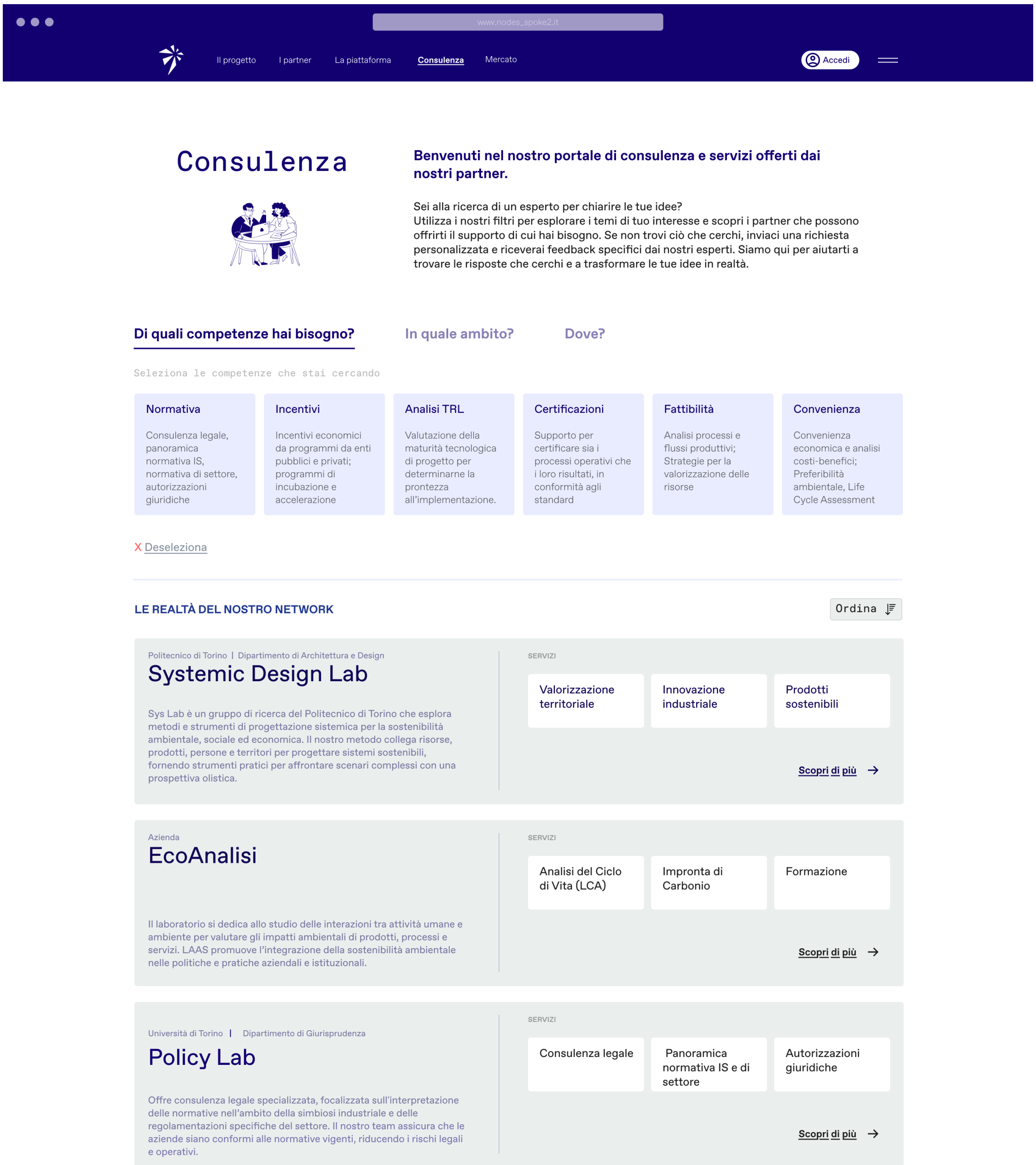

Figure 4.5: Consultancy Services Page

Chapter 5

Results and Discussion

5.1 Platform Performance Evaluation

The proposed platform for facilitating industrial symbiosis and promoting circular economy practices has been developed as a proof of concept. This section presents an evaluation of its key components and their potential impact.

5.1.1 EoW Marketplace Analysis

The EoW marketplace design demonstrates potential for connecting waste producers with potential users through its structured approach to material exchange. The evaluation suggests several promising aspects:

- **Search Optimization**: The implemented search algorithms and filtering mechanisms are designed to efficiently match waste producers with potential buyers, potentially reducing the time and effort required to find suitable matches.
- **Data Structure**: The comprehensive data model for product listings captures essential information such as material specifications, quantities, and geographical data, laying the groundwork for effective matchmaking.
- **User Interface Design**: The clean, grid-based layout implemented in Vue.js should facilitate intuitive browsing and comparison of materials, based on established UX principles.

5.1.2 User Interface Design Evaluation

The main landing page and overall interface architecture have been designed following modern web development practices and user experience guidelines. Key design considerations include:

- **Information Architecture**: The hierarchical organization of content aims to guide users naturally through the platform's core functionalities.
- **Responsive Framework**: Implementation using Vue.js and modern CSS frameworks should ensure consistent performance across different devices and screen sizes.
- **Visual Hierarchy**: The design emphasizes critical actions and information through careful use of typography, color, and spacing.
- **Performance Optimization**: The component-based architecture suggests efficient loading times and smooth interactions.

5.1.3 Consultancy Services Framework

The consultancy services module has been structured to facilitate knowledge exchange and expert support. The framework includes:

- **Expert Matching System**: The implemented algorithms for connecting users with relevant experts are based on multiple criteria including expertise, location, and specialization.
- **Knowledge Management**: The platform includes structures for organizing and presenting regulatory information and best practices.
- **Communication Framework**: The integrated messaging system should enable secure and efficient communication between users.

5.2 Discussion

The analysis of the platform suggests potential solutions to several key challenges in implementing industrial symbiosis and circular economy practices:

1. **Technical Infrastructure**: The chosen technology stack (NestJS, MongoDB, Vue.js) provides a robust foundation for scaling and adaptation as user needs evolve.
2. **Geographical Barriers**: The platform's design could help overcome geographical limitations by enabling users to identify opportunities beyond their immediate vicinity.

5.2.1 Limitations

Several aspects of the platform require validation through real-world implementation:

- **User Adoption**: The actual effectiveness of the interface design and user experience needs validation through user testing and feedback.
- **System Performance**: Real-world data volumes and usage patterns will be necessary to verify the scalability of the implemented architecture.
- **Market Dynamics**: The effectiveness of the matching algorithms in facilitating successful exchanges needs validation in a production environment.
- **Regulatory Compliance**: The platform's ability to adapt to varying regulatory requirements across different regions requires testing in actual regulatory frameworks.

While theoretically, the analysis suggests promising potential for facilitating industrial symbiosis and supporting circular economy practices, real-world implementation and user validation will be crucial for confirming these expectations. The platform's architecture and design choices provide a foundation for future development and adaptation based on user needs and market requirements.

Chapter 6

Future Work

While the platform has successfully implemented many key features, several areas still offer opportunities for improvement and further development. These enhancements will help extend the platform's capabilities and impact, particularly in the integration of emerging technologies and expanding its global reach.

6.1 Machine Learning for Predictive Analytics

The platform's rich dataset, encompassing waste generation patterns, material exchanges, and conversion processes, provides an ideal foundation for advanced machine learning (ML) applications. Drawing inspiration from the work of [10], who used ML techniques in smart waste management systems, our platform could enhance its predictive capabilities and operational efficiency. The following areas highlight the potential of ML integration.

6.1.1 Time Series Forecasting for Waste Generation

Time series forecasting is crucial for optimizing waste management operations, especially given the temporal patterns in waste generation linked to production cycles, seasonal variations, and industrial events. Building upon [11], who employed LSTM networks for waste prediction, our platform can generate reliable forecasts to support:

- **Short-term waste generation volumes**: Accurate short-term forecasts enable better optimization of collection schedules and resource allocation, leading to cost savings and increased efficiency.
- **Seasonal patterns in specific waste types**: Predicting seasonal variations in waste composition aids capacity planning and ensures adequate

infrastructure is available when most needed.

- **Long-term trends**: Identifying long-term trends informs strategic decisions like expanding recycling facilities or adjusting procurement strategies.

LSTM networks excel in time series forecasting, thanks to their ability to capture long-term dependencies in data and are ideal for capturing seasonal trends and incorporating external factors like economic conditions, providing flexibility in industrial applications.

6.1.2 Recommendation Systems for Resource Optimization

A recommendation system could significantly improve material exchanges by suggesting potential matches for users who can re-purpose or recycle waste materials. A hybrid approach, combining collaborative filtering and content-based methods, offers the most comprehensive solution:

- **Content-based filtering**: Analyzes material properties and quality to match companies with specific waste types.
- **Collaborative filtering**: Leverages historical exchange data to suggest future matches, becoming more accurate as the platform grows.
- **Matrix factorization**: Uncovers latent relationships between waste types and their potential applications.

6.1.3 Anomaly Detection for Process Optimization

Anomaly detection helps identify unusual patterns in waste management data. For example, if a factory normally produces 100kg of metal waste per day, but suddenly generates 500kg, this could indicate a problem in the production process or inefficient material use. The system can also detect environmental risks, like unexpected changes in waste toxicity levels that could be harmful. Several machine learning models could help monitor these patterns:

- **Isolation Forest**: Spots unusual waste generation amounts
- **Autoencoders**: Learns what "normal" waste patterns look like and flags anything different.
- **One-Class SVM**: Detects outliers by understanding what normal operations look like.

By detecting these issues early, companies can quickly address problems and improve their waste management processes.

6.1.4 Natural Language Processing for Knowledge Extraction

Natural Language Processing (NLP) can unlock insights from unstructured data sources such as regulatory documents and technical manuals. By integrating NLP, the platform could provide:

- **BERT-based models**: These models can extract highly specific information from large volumes of unstructured text, such as regulatory updates.
- **Named Entity Recognition (NER)**: Identifies key entities like waste materials and processes, supporting an up-to-date knowledge base.
- **Question-Answering Systems**: Offers automated responses to compliance and regulatory queries using pre-trained transformer models.

Incorporating NLP capabilities would transform the platform into a more powerful decision-support system, aiding in compliance and operational efficiency.

6.2 Blockchain for Transparency and Traceability

Integrating blockchain technology would enhance the platform's transparency and traceability, ensuring secure, immutable records of waste transactions and end-of-waste (EoW) conversions. Following the model described by [12], potential blockchain applications include:

- Smart contracts to automate waste exchange agreements and enforce compliance.
- Tokenization of waste materials for easier trading and valuation.
- Decentralized identity solutions for secure, privacy-preserving user authentication.
- Integration with IoT devices for real-time waste material tracking.

These blockchain features would build trust among users and improve accountability throughout the waste management life cycle.

6.3 Enhanced User Experience and Gamification

To increase user engagement, the platform could introduce gamification elements and improved user interface (UI) customization. Potential enhancements include:

- A points-based system rewarding users for sustainable actions.
- Virtual competitions between companies or regions to foster engagement.
- Personalized dashboards with AI-driven insights and recommendations.

These features would make the platform more interactive, user-friendly, and engaging, encouraging broader adoption.

6.4 Global Expansion and Multilingual Support

As waste management is a global challenge, expanding the platform to international markets with multilingual support is a critical future step. This could involve:

- Customizing regulatory information based on geolocation.
- Collaborations with international waste management authorities.
- Adaptation of UI to accommodate cultural and linguistic differences.
- Support for diverse units of measurement and waste classification systems.

These improvements would make the platform more accessible to a global audience and more versatile across regions.

6.5 Sustainability Impact Reporting

The platform could offer detailed sustainability reporting features, providing insights into users' environmental impact. Key features might include:

- Real-time sustainability scorecards for users and organizations.
- Predictive modeling of long-term environmental outcomes.
- Benchmarking tools to compare performance against industry standards.
- Automated report generation for regulatory and corporate sustainability reporting.

These tools would help users track their sustainability efforts and optimize their waste management strategies.

6.6 CO_2 Emission Estimation for Transportation

A valuable addition would be estimating CO_2 emissions from the transportation of waste materials. Features might include:

- Integration with mapping APIs for accurate transportation distance calculations.
- A database of emission factors for different transport modes (e.g., truck, rail).
- Route optimization for minimizing carbon footprints.
- Carbon offset recommendations based on emissions.

This feature would help users make environmentally informed decisions about waste exchanges.

6.7 Integration with Internet of Things (IoT) Devices

IoT integration could significantly enhance real-time data collection. Future possibilities include:

- Smart bins with sensors for automatic inventory updates.
- RFID tagging for tracking waste throughout the recycling process.
- Environmental sensors to monitor storage conditions of waste materials.
- Automated alerts for safety hazards or regulatory non-compliance.
- Smart city integration for optimized waste collection routing.

These additions would improve real-time monitoring and data accuracy, leading to more efficient waste management.

6.8 Advanced Data Analytics and Visualization

To provide users with deeper insights, future developments could focus on enhanced data analytics and visualization, such as:

- Predictive models for economic and environmental outcomes of waste management strategies.

- Social network analysis to identify key players in industrial ecosystems.
- Sentiment analysis of user feedback and market trends.
- Customizable dashboards for personalized data exploration.

These improvements would give users more intuitive ways to interact with complex data, driving better decision-making.

Chapter 7

Conclusion

This thesis has presented the development of a digital platform aimed at facilitating industrial symbiosis and promoting circular economy practices. Through the integration of modern web technologies and user-centered design principles, the platform demonstrates how digital innovation can contribute to addressing environmental sustainability challenges.

7.1 Key Contributions

The primary contributions of this research lie in three key areas:

1. **Technical Architecture**: The platform demonstrates an effective combination of modern technologies (NestJS, MongoDB, Vue.js) to address waste management challenges. The implemented architecture provides a foundation for future scaling and feature expansion.

2. **User Experience Design**: The development of an intuitive interface for waste exchange and expert consultation shows how thoughtful design can make complex industrial processes more accessible to stakeholders.

3. **Process Framework**: The platform provides a structured approach to industrial symbiosis, from initial waste listing through to end-of-waste conversion and expert consultation, offering a comprehensive model for digital waste management solutions.

The transition to a circular economy represents both a significant challenge and opportunity. While this platform is just one step toward addressing these challenges, it demonstrates that thoughtfully designed digital solutions can play a meaningful role in facilitating this transition. As we look to the future, the success of such initiatives will depend not only on technical implementation but also on user adoption and stakeholder engagement. The framework developed in this thesis provides a foundation for continued development in the field of industrial symbiosis and sustainable resource management.

Appendix A

User Manual

A.1 Introduction

This appendix provides comprehensive documentation for the Industrial Symbiosis Platform, a digital solution designed to facilitate industrial symbiosis and promote circular economy practices through waste-to-resource conversion and end-of-waste processes.

A.2 Getting Started

A.2.1 Registration

The registration process requires the following steps:

1. Access the platform through the secure interface
2. Select registration type (Company or Consultant)
3. Provide organizational details
4. Complete email verification
5. Submit any required documentation

A.2.2 User Roles

The platform supports two primary user classifications:

- Company: Organizations managing waste streams and transformations
  - Can create and manage multiple sites

  - Define waste outputs for each site
  - Specify waste transformation processes
  - Register desired end-of-waste inputs
- Consultant: Professionals providing waste management expertise
  - Offer recommendations and services
  - Provide expert guidance on waste management

A.3 Features

A.3.1 User Dashboard

The dashboard interface provides access to:

- Company profile management
- Site management tools
- Communication systems

A.3.2 Site Management

Users can manage multiple sites through:

- Site registration and configuration
- Waste output documentation
- Transformation process specification
- End-of-waste input requirements

A.3.3 Search Functionality

The Elasticsearch-powered search system provides:

- Full-text search capabilities
- Advanced filtering options
- Material property-based matching
- Geographic proximity search

A.4 Profile Management

A.4.1 Company Profile

Organizations can manage:

- Organizational information
- Site portfolio

A.5 Communication Tools

A.5.1 Messaging System

The platform provides:

- Secure messaging functionality
- Conversation management

This manual provides comprehensive documentation for the Industrial Symbiosis Platform, aligning with the system architecture and functionality described in the preceding chapters. It serves as a reference guide for users engaging with the platform's waste management and circular economy features.

Appendix B

API Endpoints and Database Schemas

This section provides a detailed overview of the API endpoints and the database schemas used in the system.

B.1 API Endpoints

The platform's API is structured around specific controllers, each managing a subset of the application's functionality. Here is a summary of the key controllers and their roles:

B.1.1 Core Controllers and Endpoints

Authentication Controller

Manages user authentication and session management:

```
POST /auth/login
Payload: {email, password}
Role: Public
Description: Authenticates users and issues JWT tokens

POST /auth/register
Payload: {email, password, role, displayName}
Role: Public
Description: Registers new users with validation

POST /auth/refresh
```

```
Payload: {refresh_token}
Role: Authenticated
Description: Issues new access tokens using refresh token

PUT /auth/profile
Payload: {updateData}
Role: Authenticated
Description: Updates user profile information

GET /auth/users
Role: Authenticated
Description: Retrieves list of active users for messaging
```

Messaging Controller

Handles asynchronous communication between users:

```
POST /messages
Payload: {recipientId, content, subject}
Role: Authenticated
Description: Sends a message to another user

GET /messages/inbox
Query: {page, limit, search}
Role: Authenticated
Description: Retrieves user’s received messages

GET /messages/sent
Query: {page, limit, search}
Role: Authenticated
Description: Retrieves user’s sent messages

GET /messages/:id
Role: Authenticated
Description: Retrieves specific message details

PUT /messages/:id/read
Role: Authenticated
Description: Marks message as read
```

Search Controller

Handles search operations for the platform's core entities:

```
GET /search/waste-outputs
Query: {
  q: string,              // Search query
  wasteType: string[],    // Types of waste
  location: {lat, long},  // Geographic coordinates
  radius: number,         // Search radius in km
  quantity: {min, max},   // Quantity range
  cost: {min, max},       // Cost range
  frequency: string[],    // Output frequency
  page: number,           // Page number
  limit: number          // Items per page
}
Role: Authenticated
Description: Searches for available waste outputs with filtering

GET /search/waste-transformations
Query: {
  q: string,              // Search query
  inputWaste: string[],   // Input waste types
  outputEow: string[],    // Output EoW material types
  location: {lat, long},  // Geographic coordinates
  radius: number,         // Search radius in km
  quantity: {min, max},   // Processing quantity range
  cost: {min, max},       // Processing cost range
  page: number,           // Page number
  limit: number          // Items per page
}
Role: Authenticated
Description: Searches for waste transformation processes

GET /search/eow-inputs
Query: {
  q: string,              // Search query
  materialType: string[], // EoW material types
  location: {lat, long},  // Geographic coordinates
  radius: number,         // Search radius in km
  quantity: {min, max},   // Required quantity range
  cost: {min, max},       // Target cost range
```

```
  frequency: string[],    // Input frequency
  page: number,           // Page number
  limit: number          // Items per page
}
Role: Authenticated
Description: Searches for EoW input requirements
```

Sites Controller

Manages industrial sites and their waste management associations:

```
POST /sites
Payload: {name, location, ...siteData}
Role: Authenticated
Description: Creates new industrial site

GET /sites/user/me
Role: Authenticated
Description: Retrieves all sites for authenticated user

GET /sites/:id
Role: Authenticated
Description: Retrieves specific site details

POST /sites/:id/waste-output
Payload: {wasteOutputId}
Role: Authenticated
Description: Associates waste output with site

POST /sites/:id/waste-transformation
Payload: {wasteTransformationId}
Role: Authenticated
Description: Links waste transformation to site

POST /sites/:id/eow-input
Payload: {eowInputId}
Role: Authenticated
Description: Associates EOW input with site
```

B.1.2 Waste Management Controllers

Waste Output Controller

Handles waste output records:

```
POST /waste-outputs
Payload: {wasteOutputData}
Role: Authenticated
Description: Creates new waste output record

GET /waste-outputs/:id
Role: Authenticated
Description: Retrieves specific waste output details

GET /waste-outputs
Query: {page, limit, search}
Role: Authenticated
Description: Lists all waste outputs with pagination
```

Waste Transformation Controller

Manages waste transformation processes:

```
POST /waste-transformations
Payload: {transformationData}
Role: Authenticated
Description: Records new waste transformation process

GET /waste-transformations
Query: {page, limit, search}
Role: Authenticated
Description: Retrieves all transformation records

GET /waste-transformations/:id
Role: Authenticated
Description: Retrieves specific transformation details
```

EOW Input Controller

Manages EOW input processing:

```
POST /eow-inputs
Payload: {inputData}
Role: Authenticated
Description: Creates new EOW input record

GET /eow-inputs
Query: {page, limit, search}
Role: Authenticated
Description: Retrieves all EOW inputs

GET /eow-inputs/:id
Role: Authenticated
Description: Retrieves specific EOW input details
```

B.1.3 Material Controllers

Waste and EOW Material Controllers

Handles waste and end-of-waste materials:

```
POST /eow-material
Payload: {materialData}
Role: Authenticated
Description: Creates new EOW material definition

GET /eow-material/:id
Role: Authenticated
Description: Retrieves specific EOW material details

GET /eow-material
Role: Authenticated
Description: Retrieves all EOW material details

POST /waste
Payload: {wasteData}
Role: Authenticated
Description: Creates new waste definition

GET /waste/:id
Role: Authenticated
Description: Retrieves specific waste details
```

```
GET /waste
Role: Authenticated
Description: Retrieves all waste details
```

B.2 Database Schemas

The database is organized around MongoDB collections, with each collection representing a distinct entity within the platform. Despite MongoDB's schema-less nature, we implement application-level schemas to ensure data consistency and integrity. The following details the structure of each collection:

User Collection

```
{
    _id: ObjectId,
    username: { type: String },
    email: { type: String },
    password: { type: String },
    userType: { type: String, enum: ['company', 'consultant'] },
    registrationDate: { type: Date, default: Date.now },
    refreshToken: { type: String }
}
```

Site Collection

```
{
    _id: ObjectId,
    address: { type: String },
    city: { type: String },
    state: { type: String },
    zip: { type: String },
    country: { type: String },
    coordinates: [Number],  // [longitude, latitude]
    user: { type: ObjectId, ref: 'User' },
    inputs: { type: [ObjectId], ref: 'EOWInput' },
    transformations: { type: [ObjectId], ref: 'WasteTransformation' },
    outputs: { type: [ObjectId], ref: 'WasteOutput' }
}
```

Waste Collection

```
{
    _id: ObjectId,
    name: { type: String },
    description: { type: String },
    image: { type: String }
}
```

EOWMaterial Collection

```
{
    _id: ObjectId,
    name: { type: String },
    description: { type: String },
    image: { type: String }
}
```

WasteOutput Collection

```
{
    _id: ObjectId,
    outputWaste: { type: ObjectId, ref: 'Waste' },
    quantity: { type: Number },
    frequency: { type: String },
    cost: { type: Number },
    site: { type: ObjectId, ref: 'Site' }
}
```

WasteTransformation Collection

```
{
    _id: ObjectId,
    inputWaste: { type: ObjectId, ref: 'Waste' },
    outputEowMaterial: { type: ObjectId, ref: 'EOWMaterial' },
    quantity: { type: Number },
    cost: { type: Number },
    site: { type: ObjectId, ref: 'Site' }
}
```

EOWInput Collection

```
{
    _id: ObjectId,
    inputEowMaterial: { type: ObjectId, ref: 'EOWMaterial' },
    quantity: { type: Number },
    frequency: { type: String },
    cost: { type: Number },
    site: { type: ObjectId, ref: 'Site' }
}
```

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