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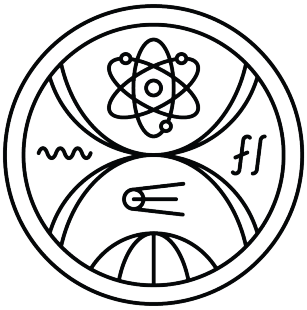

ANALYSIS, DESIGN AND IMPLEMENTATION OF MICRO-FRONTEND ARCHITECTURE

Diploma thesis

2025 Bc. Pavol Repiský

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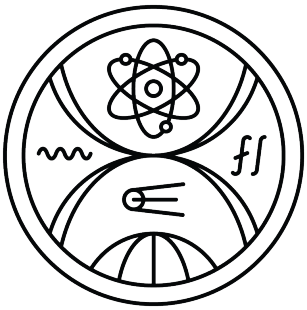

ANALYSIS, DESIGN AND IMPLEMENTATION OF MICRO-FRONTEND ARCHITECTURE

Diploma thesis

Study program:	Applied Computer Science
Branch of study:	Computer Science
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Bratislava, 2025 Bc. Pavol Repiský

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ZADANIE ZÁVEREČNEJ PRÁCE

Meno a priezvisko študenta: Bc. Pavol Repiský
Študijný program: aplikovaná informatika (Jednoodborové štúdium, magisterský II. st., denná forma)
Študijný odbor: informatika
Typ záverečnej práce: diplomová
Jazyk záverečnej práce: anglický
Sekundárny jazyk: slovenský

Názov: Analysis, Design and Implementation of Micro-frontend Architecture
Analýza, návrh a implementácia mikrofrontendovej architektúry

Anotácia: Mikrofrontendy predstavujú ďalší logický krok vo vývoji architektúry webových aplikácií. Tento prístup si však vyžaduje zvýšenie zložitosti architektúry a vývoja projektu. Problémy ako smerovanie, opätovná použiteľnosť, poskytovanie statických aktív, organizácia úložiska a ďalšie sú stále predmetom značnej diskusie a komunita ešte musí nájsť riešenia, ktoré dokážu efektívne spustiť projekt a riadiť výslednú zložitosť. Aj keď boli navrhnuté a diskutované niektoré prístupy, existuje veľké množstvo poznatkov a potenciálu na objavenie nových prístupov.

Cieľ: Preskúmajte existujúcu literatúru o prístupoch k návrhu a vývoju webových aplikácií pomocou mikro-frontend architektúry.
Porovnajte existujúce prístupy z hľadiska opätovnej použiteľnosti, rozšíriteľnosti, zdieľania zdrojov a správy stavu aplikácií.
Identifikujte prístupy, ktoré sú najvhodnejšie pre vývoj podnikových aplikácií, potom navrhnite a implementujte prototypovú mikrofrontendovú aplikáciu pomocou jedného vybraného prístupu.

Literatúra:
https://www.researchgate.net/publication/351282486_Micro-frontends_application_of_microservices_to_web_front-ends
https://www.angulararchitects.io/blog/micro-apps-with-web-components-using-angular-elements/
https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1570726&dswid=5530
https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1778834&dswid=-4588
https://www.scientificbulletin.upb.ro/rev_docs_arhiva/reze1d_965048.pdf

Vedúci: RNDr. Ľubor Šešera, PhD.
Konzultant: Ing. Juraj Marák
Katedra: FMFI.KAI - Katedra aplikovanej informatiky
Vedúci katedry: doc. RNDr. Tatiana Jajcayová, PhD.

Spôsob sprístupnenia elektronickej verzie práce:
bez obmedzenia

Comenius University Bratislava
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THESIS ASSIGNMENT

Name and Surname:	Bc. Pavol Repiský
Study programme:	Applied Computer Science (Single degree study, master II. deg., full time form)
Field of Study:	Computer Science
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Language of Thesis:	English
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Title: Analysis, Design and Implementation of Micro-frontend Architecture

Annotation: Micro-frontends represents the next logical step in the development of a web-application architecture. However, this approach necessitates an increase in the complexity of the project architecture and development. Issues such as routing, reusability, static asset serving, repository organization, and more are still the subject of considerable discussion, and the community has yet to find any solutions that can effectively bootstrap a project and manage the resulting complexity. While there have been some approaches proposed and discussed, there is a great deal of knowledge and potential for new approaches to be discovered.

Aim: Review existing literature about approaches to design and development of web applications using micro-frontend architecture.
Compare existing approaches from aspects of reusability, extendibility, resource sharing and application state management.
Identify approaches best suited for enterprise application development, then design and implement a prototypical micro-frontend application using one selected approach.

Literature:
https://www.researchgate.net/publication/351282486_Micro-frontends_application_of_microservices_to_web_front-ends
https://www.angulararchitects.io/blog/micro-apps-with-web-components-using-angular-elements/
https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1570726&dswid=5530
https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1778834&dswid=-4588
https://www.scientificbulletin.upb.ro/rev_docs_arhiva/reze1d_965048.pdf

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Assigned: 05.10.2023

Approved: 05.10.2023 prof. RNDr. Roman Ďurikovič, PhD.
Guarantor of Study Programme

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Abstrakt

Táto práca podrobne analyzuje niekoľko najpoužívanejších prístupov k mikrofrontendom a porovnáva ich na základe aspektov, ako sú rozšíriteľnosť, opätovná použiteľnosť, jednoduchosť, výkon, zdieľanie zdrojov a skúsenosti vývojárov. Každý z týchto prístupov je dôkladne posúdený z hľadiska jeho výhod, nevýhod a použiteľnosti. Jeden z týchto prístupov, konkrétne web-compoents, bol zvolený na implementáciu proof-of-concept aplikácie pre manažovanie projektov vo frameworku Angular. Počas jej vývoju sme narazili na niekoľko bežných problémov, ako sú kompozícia, zdieľanie zdrojov, smerovanie a izolácia, ktoré sme vyriešili a riešenia uvádzame priamo v práci.

Výsledky implementácie naznačujú, že webové komponenty sú v efektívnym a dobrým prístupom k implementácii mikrofrontendovej architektúry. Prinášajú však niekoľko výziev, z ktorých hlavnými sú riešenie spoločných závislostí a komunikácia medzi mikroaplikáciami. Úspešné adoptovanie tejto architektúry si preto vyžaduje dôkladné plánovanie. Zistenia tejto práce poskytujú cenné poznatky o týchto výzvach a ich riešeniach. Okrem toho zjednodušujú rozhodovanie vývojárom a organizáciám, ktoré zvažujú túto architektúru pre svoje projekty.

Kľúčové slová: Microfrontends, Web-components, architektúry webových aplikácií, Angular

Abstract

This paper analyzes in detail several of the most widely used approaches to micro-frontends and compares them based on aspects such as extensibility, reusability, simplicity, performance, resource sharing, and developer experience. Each of these approaches is thoroughly assessed in terms of its advantages, disadvantages and usability. One of these approaches, namely web-compoints, was chosen to implement a proof-of-concept project management application in the Angular framework. During its development, we encountered several common issues such as composition, resource sharing, routing, and isolation, which we solved and will present solutions directly in the thesis.

The implementation results suggest that web components are an efficient and good approach to implement a micro-frontend architecture. However, they present several challenges, the main ones being the sharing of common dependencies and communication between micro-applications. Successful adoption of this architecture therefore requires careful planning. The findings of this work provide valuable insights into these challenges and their solutions. In addition, they simplify decision making for developers and organizations considering this architecture for their projects.

Keywords: Microfrontends, Web-components, web application architectures, Angular

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Chapter 1

Introduction

This chapter provides a brief introduction to microfrontends and the motivations behind this thesis. It also offers a brief overview of the existing literature on microfrontends. Then it presents the aim of the thesis and finally, it acknowledges its scope and limitations.

1.1 Background and Motivation

Microfrontends are one of the most promising directions in frontend development of modern software applications. They are based on the same idea as the more well-known microservices: splitting a software application into several separate smaller, independent applications to better address issues such as complexity, maintainability and deployability [1][2][3].

While microservices focus on the partitioning the application layer, microfrontends deal with the partitioning of the frontend (presentation) layer of an application. Thus, despite some similarities, microservices and microfrontends address a different set of problems and use different techniques and technologies. Another important difference is that there are several accepted principles and patterns in microservices [4][5]. In microfrontends, there is not yet a general consensus on which of the principles is most appropriate, nor is there a set of design patterns for microfrontends.

Several articles [3][6][7][8] have been written on different approaches to microfrontends. However, each of these articles explains the approaches only briefly and does not analyze them in depth nor compare them with each other. An overview work on the basic approaches to microfrontends has been provided by Geers [2] in his book *Micro Frontends in Action*. This book not only summarized the basic approaches to creating microfrontends and provided simple examples, but also compare them at a general

level. On the other hand, the examples given in the book are too simple for enterprise applications, and even the comparison of approaches is left at a rather general level. The same can be said about the book *Building Micro-Frontends* by Mezzalira [1].

1.2 Aim

The aim of this thesis is to review the current literature on existing approaches to creating microfrontends, and analyze in depth and compare these approaches from the perspective of enterprise applications in aspects such as reusability, extensibility, resource sharing, and application state management.

Subsequently, one of these prospective approaches will be selected to validate its suitability and correctness by implementing a simple prototype microfrontend application implemented in an enterprise technology such as Angular [9] or React [10]. Finally, conclusions will be drawn and the chosen approach will be evaluated.

1.3 Scope and Limitations

Due to the breadth of the topic of microfrotends, the thesis will not cover all the important aspects of this architecture. Furthermore, it will not cover all possible existing approaches to implementing microfrontends, focusing on selecting those that are most commonly mentioned in the literature and used in practice.

The resulting application will serve as a proof of the validity of the chosen approach, not as a fully deployable solution for real-world use. The development of the application will be limited by time and available resources, which will affect its complexity and scope. The findings and conclusions drawn may not be generally applicable to all scenarios.

Chapter 2

Microservices and Microfrontends

This chapter introduces the concept of microservices and microfrontends, starting with theirs brief history. It futher explores the fundamental principles of microservices and how they apply to microfrontends. It also describes the challenges, advantages, and disadvantages of microfrontends. Finally, it concludes with real-world examples of microfrontend adoption.

2.1 History of Microservices and Microfrontends

By the beginning of this millennium, some software systems had become so large that they became difficult to maintain. The most famous example is *Amazon*'s [11] eshop, which went into critical condition in 2002. Hundreds of developers worked on the system. Although the system was divided into layers and components, these components were tightly interconnected. The development of a new version of the system was slow and deployment took on the order of weeks. Amazon then came up with a key solution: splitting the monolithic application into separately deployable services and creating an automated pipeline from build to deployment of the application [12].

Amazon's example was later followed by other companies such as *Netflix* [13], *Spotify* [14], *Uber* [15] and others [16]. In 2011, the first stand-alone workshop on this new approach to architecture was held near Venice. The workshop called this new architectural style *Microservices* [17]. In 2014, James Lewis and Martin Fowler wrote a blog in which they generalised the ideas from the workshop. In the article, they defined what Microservices are and specified their basic characteristics [17]. The article popularized Microservices in the general professional community. In 2015, Sam Newman wrote the first book on microservices, *Building Microservices* [5]. In parallel, Chris Richardson created his website [18] in 2014. He later compiled the ideas from this site into a separate book *Microservices Patterns* [4].

The term *Microfrontends* first appeared in the *ThoughtWorks Technology Radar* magazine [19] at the end of 2016, through 6 subsequent editions it has climbed from the Asses, Trial to the Adopt section. They described it as the application of microservices concepts to the frontend. Ideas from this magazine were further developed by Cam Jackson in an article *Micro Frontends* published on the Martin Fowler website. Another major milestone was the creation of a website on the topic of micro frontends by Michael Geers' [20] in 2017. Later in 2021, he compiled this site into a comprehensive, monograph, *Micro Frontends in Action* [2]. In 2021, a second monograph by Luca Mezzaliro, *Building Micro-frontends*, was published, further exploring this architecture. From the history, we see that Microfrontends are following a very similar path to microservices.

2.2 Microservices Principles

This section summarizes the basic principles of microservices architecture based on Martin Fowler's article [17] and Sam Newman's book [5].

2.2.1 Componentize via Services

The primary way of componentizing microservices applications is by breaking them down into services. Applications built this way aim to be as decoupled and cohesive as possible, where each service acts more like a filter in the Unix sense—receiving a request, applying some logic, and producing a response. The services communicate using REST protocols or a lightweight message bus. For this to work in practice, we must create a loosely coupled system where one service knows very little or nothing about others. This combination of related logic into a single unit is known as cohesion. The higher the cohesion, the better the microservice architecture.

2.2.2 Model Around Business Domain

Traditionally, applications were split into technical layers such as the Presentation Layer, Business Layer, and Data Access Layer, with each of these layers being managed as a separate service by its own team. The problem with this approach is that making even a small change often cascades across multiple layers and teams, resulting in several deployments. This challenge worsens as more layers are added. This is known as horizontal decomposition. Opposite to this is vertical decomposition, which focuses on finding service boundaries that align with business domains. This results in services with names reflecting the system's functionalities and exposing the capabilities that

customers need. Therefore, changes related to a specific business domain tend to affect only the corresponding service boundary rather than multiple services. The team owning the service becomes an expert in that domain. Additionally, this approach ensures loose coupling between services and enhances team autonomy.

2.2.3 Design for Failure

Microservices aim to enhance the fault tolerance and resilience of an application by isolating services to prevent the failure of one service from cascading to others. Microservices should be designed with the assumption that any service can fail at any time. To ensure this, different patterns are utilized, such as the circuit breaker pattern. If a microservice fails repeatedly, the circuit breaker pattern allows the system to temporarily cut off communication with the problematic service, thereby preventing repeated communication attempts with the failing service and avoiding potential performance issues and application-wide failures. This enables other services to function properly without disruption, improving overall system resilience.

2.2.4 Adopt a Culture of Automation

Microservices add a lot of additional complexity because of the number of different moving pieces. Embracing a culture of automation is one way to address this, and front-loading effort to create automation tooling makes a lot of sense. One such tooling is automated testing at various levels (unit, integration, end-to-end) to ensure code quality is maintained. Another key aspect of automation is continuous integration and continuous deployment (CI/CD), where code changes are automatically built, tested, and deployed to production. Infrastructure as Code (IaC) is another important aspect. It enables teams to define and manage infrastructure via code, ensuring that environments are consistent, easily reproducible, and scalable. Automation enhances productivity, speeds up development, minimizes errors and frees teams from repetitive tasks.

2.2.5 Decentralize Everything

One of the problems with centralized governance is the tendency to standardize on a single technology, which may not be the best fit for every problem, as there may be better choices available. Microservices aim to avoid this by encouraging developers to use different technologies and frameworks based on what they believe will be the best tool for a given service. Each service typically also manages its own data storage, whether through different instances of the same technology or entirely different systems. Teams take complete ownership of their services through decentralized decision-making,

becoming domain experts in both the service and the related business domain they are supporting. By decentralizing everything—from decision-making and development to infrastructure and data management—we create systems that are more scalable, resilient, and adaptable.

2.2.6 Evolve Continuously

Microservices embraces the idea that software systems should keep evolving to meet new requirements, technologies, and business needs. This aligns well with the architecture, as each service is built and deployed independently and therefore can evolve at its own pace without requiring redesigns of the entire system. Additionally, new features can be added and plugged in as completely new services. This allows organizations to adapt quickly to changing requirements and grow with the needs of the business, ensuring long-term sustainability.

2.3 Introduction to Microfrontends

The main idea behind microfrontends is to extend the principles of microservices to the frontend side [7][2]. In microfrontends, the presentation layer is split into smaller, more manageable pieces [7]. Jackson [8] describes microfrontends as: "An architectural style where independently deliverable frontend applications are composed into a greater whole." Each microfrontend can be developed, tested, and deployed independently while still appearing to customers as a single cohesive product [8].

As Geers [2] describes, microfrontends are not just an architectural approach but also an organizational one. Microfrontends can be combined with microservices on the backend, resulting in a system divided into a number of full-stack micro-applications [7], as shown in Figure 2.1. Each such micro-application is autonomous, with its own continuous delivery pipeline and serving a specific business domain or feature [6]. Microfrontends introduce vertical teams instead of horizontal ones. Instead of being grouped by the development technologies they use, teams are grouped by application features [7]. Each team works on a single full-stack micro-application, developing it all the way from the presentation layer to its data layer. The team takes complete ownership of the feature, decentralizing decision-making and determining what technology to use.

Figure 2.1: Architectural overview of microfrontends

2.4 Microfrontends Challenges

This section presents inevitable challenges that need to be addressed when building microfrontends applications.

2.4.1 Communication

In an ideal world, we would want microfrontends to not communicate with each other at all. However, in real-world applications, that is not the case, especially when multiple microfrontends are on the same page. In traditional architectures, such as Single Page Applications, components communicate via direct parent-to-child data binding (e.g., props), child-to-parent callbacks, or shared state management solutions. However, this type of direct communication is not possible between microfrontends, as they are decoupled and independent.

There are several options for handling communication, with the most suitable one depending on the project type and chosen composition approach. Here are the most commonly mentioned ones. The first option is to inject an event bus, to which all microfrontends can send and receive events. To inject the event bus, we need the microfrontend container to instantiate it and inject it into all of the page's microfrontends [1]. The second option is a variation of the previous one, where we utilize Custom Events [1][2]. Most browsers now also support the new *Broadcast Channel API* [21],

which allows the creation of an event bus that spans across browser windows, tabs, and iframes [2]. Lastly, there are less flexible and secure options, such as communication via query strings [1] or utilizing web storage.

2.4.2 Routing

As microfrontends should be independent, isolated, and developed without prior knowledge of how they will be deployed, the next challenge is how to handle application routing, including the management of the currently active microfrontend. The solution will again depend on the chosen composition approach.

As Mezzalira [1] describes it, in the case of server-side composition, all the logic to build and serve the application happens on the server; therefore, routing must also be handled here. When a user requests a page, the server retrieves and combines different microfrontends to generate the final page. Since every request goes back to the server, it must be able to keep up with all the requests and scale well. This scaling issue can be improved by storing copies of the pages on a CDN; however, this will not work for dynamic or personalized data. When using edge-side composition, the composition happens at the CDN level. CDN knows which microfrontends to combine to serve the page based on the current URL. This is done through a technique called transclusion, where different microfrontends are stitched together. These two types of routing are best for applications that need to change views based solely on the current URL and for teams with strong backend skills [1].

Finally, there is the possibility of using client-side routing. In this case, the application shell will handle all routing and load different microfrontends based on the user state (such as whether the user is authenticated or not) and the current URL. This is a perfect approach for more complex routing based on different factors beyond just the URL and for teams with stronger frontend skills [1]. Additionally, the approaches can also be combined, such as CDN and origin or client-side and CDN [1].

2.4.3 Static Assets Serving

Static asset serving can also present a challenge in microfrontends due to each microfrontend having its own autonomous deployment. One issue arises from potential namespace conflicts, where multiple microfrontends may use the same filenames, leading to unintended overwrites or collisions. This can be avoided by strict naming conventions. Another issue is security concerns, such as Cross-Origin Resource Sharing (CORS) issues, which require careful configuration of asset access policies. Finally, microfrontends deployed on different domains or environments may face difficulties in

locating and serving static files.

Potential solutions include a predefined deployment structure, where all static files are placed in specific directories, or creating a system-wide shared function that dynamically returns the resource location based on the context and state of the system [3]. Also each microfrontend can request its assets via an HTTP request independently, or in the case of small assets, they can be bundled inside the microfrontend itself.

2.4.4 Reusability

Microfrontends introduce a lot of code redundancy, as many components must be implemented in multiple microfrontends repeatedly. This can be somewhat mitigated by using shared dependencies. However, this introduces another issue: without proper handling, each microfrontend might bundle the same dependency, increasing the overall bundle size and load time. Additionally, if microfrontends use different technologies or versions, inconsistencies across the libraries may occur. Some libraries provide solutions to the first issue, such as Webpack's Module Federation, which offers shared dependency management even for different dependency versions. However, there are currently no no universal solutions, and each project must be assessed individually.

2.4.5 Styling Consistency and Isolation

Since all microfrontends are developed by an autonomous team, the user interface (UI) and user experience (UX) can differ significantly in each one of them. Therefore, there needs to be a common design system to ensure UI and UX consistency across all microfrontends. As mentioned in Peltonen's study [6], one possible approach is to use a shared CSS stylesheet. However, this would mean that all applications depend on a single common resource, which goes against the principle of loose coupling. Another option is to use a common component library, but if the microfrontends are developed using different technologies, the library must be available for in of them. A more universal solution is to use a common style guide, such as Bootstrap or Material Design, which helps maintain a consistent, though not identical, look and feel across the entire application.

Another styling challenge that needs to be addressed is style isolation within each microfrontend to prevent styles from one microfrontend overriding styles in another. This issue is particularly relevant for microfrontends composed on the client-side since server-side microfrontends are composed before reaching the browser and can be better isolated. There are two main solutions to this problem. The first involves using unique class naming conventions, such as prefixing class names with the microfrontend's name.

Alternatively, there are libraries that handle this automatically. The second solution is utilizing the Shadow DOM, particularly when using web-components for composition.

2.4.6 Project Organization

A monolithic system can be easily stored in a single repository inside a Version Control System (VCS), but with microfrontends, it becomes more complex. Generally, there are three types of repositories that can be utilized: mono-repository, multi-repository, and multi-repository with the git-repo tool [3].

As Pavlenko [3] puts it, the simplest way is to use a mono-repository and place all microfrontends in a single repository, structured into folders. The problem with this approach is that each developer must download the entire codebase, even if they are only working on one microfrontend. This can be quite large in the case of complex projects. Additionally, branch checkouts and synchronizations can take a lot of time. The second approach is to have separate repositories for each microfrontend and potentially also for common parts. Microfrontends would then be published as packages in a private package registry and linked to the project via it. However, this increases the complexity of developer tools and maintenance [3].

The last approach is to again have multiple repositories, but manage them via the git-repo tool. The developer provides a configuration file to the tool, which describes which repositories should be downloaded and how they should be structured. The tool then performs the necessary actions. With this approach, developers can download only the necessary parts of the codebase, and the issue of slow checkouts is also removed, as synchronization happens only between the chosen repositories. Additionally, it does not require a package registry. However, the complexity is still higher than in the case of a mono-repository [3].

2.5 Microfrontends Tradeoffs

This section lists the most frequently mentioned advantages and disadvantages of microfrontends in the literature.

2.5.1 Advantages

There are numerous reasons why large companies are adopting microfrontend architecture, but the most prominent one is the increased development speed and reduced time to market due to cross-functional teams [2][7][6]. Geers [2] mentions: "Reducing

waiting time between teams is microfrontends' primary goal." Having all developers working on the same stack within a single team leads to fewer misunderstandings and much faster communication [2][7]. Additionally, teams have much more freedom to make case-by-case decisions regarding individual parts of the product [8][2], allowing teams to become experts in their respective areas of the application [7].
Microfrontends also bring many of the benefits of microservices architecture to the frontend. The codebases are smaller, more understandable, and less complex [2][8][7]. Consequently, this can lead to shorter onboarding times for new developers [6]. Each microfrontend is isolated, independently deployable, and its failure does not affect the rest of the system [6][7][8][2].

Microfrontends encourage changes and experimentation with new technologies, which is especially important in the frontend space, where technologies evolve rapidly. Microfrontends provide a way to upgrade only specific parts of the application instead of rewriting the entire system at once [8][7], and each microfrontend can potentially be developed using different technologies. This encourages developers to experiment with new tools and quickly adapt to changing requirements [6].

2.5.2 Disadvantages

However, microfrontends are not a silver bullet. Having an application split into multiple parts across multiple teams, potentially using different technologies, naturally introduces a lot of redundancy. The redundancy can be in terms of actual code, where multiple teams implement the same functionality repeatedly, but also in terms of common dependencies, which, if not handled properly, will be included in multiple microfrontends. Furthermore, if teams are using different technologies or even just different versions, they must all be bundled individually [2][6]. This all leads to a larger payload size, with the browser having to fetch more data, which can negatively affect the performance of the application [6][7][8]. Each team also needs to set up and maintain its own application server, build process, and CI/CD pipelines.

As already mentioned in the challenges section 2.4, this architecture also complicates otherwise well-established techniques such as routing, communication, static asset serving, and styling, requiring them to be handled in a specialized way.

Microfrontends can potentially add a lot of unnecessary complexity at both the technical and organizational levels [6]. They require a significant amount of knowledge and analysis about a project before development begins [7][6]. There are risks associated with developing in a standalone environment that is quite different from production,

requiring extensive integration testing [8][7][6]. This differs from microservices, as they do not need to be integrated into a single application. Lastly, microfrontends could potentially lead to varying code quality if requirements are not clearly defined across all teams [7].

2.6 Microfrontends in Practice

This section presents a list of well-known medium and large companies that have adopted microfrontends as their main system for scaling their business further.

Amazon

The first noteworthy example is Amazon [11]. Although Amazon does not often publicly share its internal architecture, according to Geers [2], several Amazon employees have reported that the e-commerce site has been using this architecture for quite some time. Amazon supposedly employs a UI composition technique that assembles different parts of the page before it is displayed to the customer.

IKEA

Another well-known e-commerce platform is IKEA [22]. IKEA's principal engineer, Gustaf Nilsson Kotte, shares in an interview [23] that they started experiencing the same problems with the frontend monolith as they had with the backend monolith. This led them to adopt the microfrontend architecture. They decided to use the Edge Side Includes (ESI) composition approach and introduced the concept of pages and fragments. Pages can contain ESI references to fragments. The fragments are self-contained, meaning they include everything they need, such as CSS and JavaScript, and are reused across multiple pages. Teams are responsible for a set of pages and fragments.

Zalando

The European fashion e-commerce platform Zalando [24] has also adopted microfrontends. Zalando even open-sourced its microfrontend framework, "Tailor.js" [25], which was later replaced by the Interface framework. Compared to Tailor.js, the Interface framework is based on similar concepts but is more focused on components and GraphQL instead of fragments [1].

Spotify

An example of an unsuccessful adoption is Spotify [14]. As Mezzalira [1] describes, their desktop application initially used iframes to compose the UI, communicating via a "bridge" for the low-level implementation made with C++. Spotify also attempted to use this approach when developing the web version of the Spotify player but abandoned it due to poor performance. Since then, they have reverted to a single-page application (SPA) architecture.

SAP

Next on the list is SAP [26]. SAP initially utilized iframes and eventually released its own microfrontend framework, "Luigi" [27], designed for creating enterprise applications that integrate with SAP systems. It supports modern enterprise frontend frameworks such as Angular, React, Vue, and SAP's own SAPUI [1].

DAZN

The last on the list is DAZN [28], a sports streaming platform. DAZN has migrated its monolithic frontend to a microfrontend architecture [2]. The company focused on supporting not only the web but also multiple smart TVs and gaming consoles [1]. They chose a client-side approach to composition. As Mezzalira [1] describes, the platform uses a combination of SPAs and components orchestrated by a client-side agent called "Bootstrap". They have shared their experiences with microfrontends extensively and eventually even published a book on the topic [1].
These are just a few of the most significant examples, but there are many more. And more and more companies are beginning to adopt this architecture.

Chapter 3

Microfrontends in Detail

This chapter provides a deeper exploration of microfrontends architecture, offering readers a solid foundation to understand not only what microfrontends are but also the key approaches to implementing them effectively.

3.1 Basic Enablers of Microfrontends

In this section, we introduce key technologies that may be unfamiliar to the reader but will be used for implementing microfrontends and will be referenced frequently throughout the thesis.

3.1.1 Web Components

Web Components are a set of web platform APIs that allow developers to create reusable, encapsulated, and customizable HTML elements [29]. They are now supported by most major browsers and work across different frameworks and libraries [30]. We will now discuss the three main technologies that make up Web Components.

HTML Templates

HTML templates are a new addition to the HTML language. They allow us to define reusable HTML structures that are not immediately rendered in the document. Instead, they remain inactive until they are cloned via JavaScript [29]. To create such a structure, we utilize the `<template>` element.

```
<template id="my-template">
  <p>Some content goes here...</p>
</template>
```

Then, we can clone the template and add it to the DOM via JavaScript.

```
let template = document.getElementById("my-template");
let clone = template.content.cloneNode(true);
document.body.appendChild(clone);
```

A `<slot>` element can be used inside the template as a placeholder for content passed from the outside. If no content is provided, a default fallback value can be specified. Templates and slots can then be used inside a custom element as the basis of its structure [29].

Custom Elements

Custom elements are a set of JavaScript APIs for creating custom HTML elements with specific behavior [29]. To register a custom element, we use the `customElements` global object and its method `define`, to which we pass a hyphenated tag name and a class that inherits from the `HTMLElement` class.

```
customElements.define(
  "my-element",
  class MyElement extends HTMLElement {}
);
```

Lifecycle hooks can then be leveraged inside the class to adjust its behavior, such as:

- `connectedCallback()` - this lifecycle hook is fired when the element is connected to the DOM,
- `disconnectedCallback()` - this lifecycle hook is fired when the element is disconnected from the DOM,
- `attributeChangedCallback(name, oldValue, newValue)` - this lifecycle hook is fired whenever one of the observed attributes is changed.

To define the content of a custom element, we assign an HTML string to its `innerHTML` property. The element can then be used inside an HTML document like any other element.

```
<my-element attribute="value"></my-element>
```

Shadow DOM

Lastly Shadow DOM is a set of JavaScript APIs that enables us to attach an encapsulated "shadow" DOM subtree to an element, which is then rendered separately from the main document DOM [29]. The styles and scripts placed inside it do not leak out and affect the surrounding DOM, nor do outside styles and scripts leak into it.

This way, we do not have to worry about collisions with other parts of the document [30]. To use Shadow DOM inside a custom element, we must first attach it by calling `attachShadow(options)` and specifying the mode (`open` or `closed`), then append whatever content we want to it.

```
class MyElement extends HTMLElement {
  constructor() {
    super();
    let shadow = this.attachShadow({ mode: 'open' });
    let div = document.createElement('div');
    div.textContent = "Some content goes here...";
    shadow.appendChild(div);
  }
}
```

Open Shadow DOM can be accessed via JavaScript using `element.shadowRoot`. Closed Shadow DOM cannot be accessed externally using `element.shadowRoot` [29].

3.1.2 Custom Events

Unlike built-in events like `click` or `keydown`, custom events do not natively exist in the browser but are created and dispatched manually via JavaScript. Custom events allow developers to define their own event names and pass any custom data [31]. The `CustomEvent` constructor is used to create such events, to which we pass an event name and an optional object where we can specify the data we want to send and the properties of the event, such as following.

- `bubbles: true` - Allows the event to propagate upward to the parent element. This is set to `false` in custom events by default. The propagation can be stopped using `stopPropagation()` method.
- `cancelable: true` - Allows the event to be canceled via `preventDefault()` method.
- `composed: true` - Allows the event to propagate from the shadow DOM to the real DOM. In this case, the `bubbles` property must be set to `true` [32].

Putting it all together, we would create a custom event as follows.

```
let myEvent = new CustomEvent("my-event", {
  detail: {key: "value"},
  bubbles: true,
  cancelable: true,
```

```
  composed: false,
});
```

The event can then be dispatched on a specific element using `dispatchEvent()` method.

```
document.dispatchEvent(myEvent);
```

We can listen for the event using `addEventListener()` method.

```
document.addEventListener("my-event", function (e) {
  console.log("My event value:", e.detail.key);
});
```

3.2 Composition Approaches

There are multiple approaches to implementing microfrontends. Some are as simple as linking between different applications, while others could fill an entire book. However, the important thing to note is that there is no single best approach, the most suitable one depends on the project requirements and the team's knowledge.

This section introduces six of the most commonly mentioned approaches in the literature, outlining their advantages, disadvantages, and suitability. Based on both the reviewed literature and our own insights, each approach is rated on a scale from 1 (lowest) to 5 (highest) across the following aspects.

- **Extensibility**
  - 1: A tightly coupled, monolithic-like frontend where adding a new microfrontend requires modifying other parts of the codebase.
  - 5: A modularized approach where new microfrontend can be easily added without affecting existing ones.
- **Reusability**
  - 1: Microfrontends have minimal or no customization options
  - 5: Each microfrontend is highly customizable to fit different environments.
- **Simplicity**
  - 1: Complex integration requiring custom solutions and extensive boilerplate code.
  - 5: A straightforward, declarative composition approach with minimal extra configuration.

- **Performance**
  - 1: Adding a new microfrontend significantly impacts performance.
  - 5: Performance remains comparable to or better than a SPA.
- **Resource Sharing**
  - 1: Each microfrontend loads its own separate versions of frameworks, styles, and assets.
  - 5: Common dependencies and assets can be efficiently deduplicated.
- **Developer Experience**
  - 1: A complex and unfamiliar local development setup.
  - 5: A streamlined development process similar to established web development techniques such as single-page applications (SPA) or server-side rendering (SSR).

3.2.1 Link-based Composition

The simplest approach to a microfrontend architecture in this list is the composition of multiple applications using hyperlinks. In this approach, the application is split into multiple microfrontends, which are developed completely separately by dedicated teams. Each application brings its own HTML, CSS, and JavaScript files and is deployed independently, typically on a different port under the same domain, ensuring it remains fully isolated from other applications in the system [2]. To compose the microfrontends, we simply interconnect them across different applications using standard anchor elements.

```
<a href="https://example.com/mfe2">View</a>
```

The teams must therefore share all URL patterns of their applications, which will be used to link their sites from other teams' applications [2]. Examples of such URL patterns might look like the following:

- **Team A - Microfrontend 1**
  URL pattern: `https://example.com/mfe1`
- **Team B - Microfrontend 2**
  URL pattern: `https://example.com/mfe2`

Rather than exchanging these URL patterns verbally, which would require informing all affected teams and potentially redeploying their applications when URLs change,

a better solution is to maintain a centralized JSON file containing all URL patterns for each team. Other applications can then read this file at runtime to construct the necessary URLs [2].

Advantages

This composition method offers a couple of unique advantages. It provides complete isolation between microfrontends like no other approach discussed here. Errors in one microfrontend are contained and do not affect any other parts of the system. The microfrontends can be deployed independently, and the project requires minimal extra configuration. The system can be easily expanded by adding new microfrontends [2].

Disadvantages

As Geers [2] mentions, the primary limitation of this approach is that it does not allow for the composition of multiple microfrontends on a single page. Users must click through links and wait for page loads when navigating between different sections, potentially worsening the user experience. Additionally, common elements, such as headers, need to be reimplemented and maintained separately within each microfrontend, leading to code duplication, maintenance overhead, and potential inconsistencies. Resource sharing between microfrontends is also very complex.

Suitability

While microfrontend composition via links provides a basic integration strategy, it is rarely used as the sole approach in modern web development due to its limitations. It is typically combined with other techniques to create more robust solutions [2]. Our evaluation of this approach can be found in the table 3.1.

Aspect	**Rating**
Extensibility	4/5
Reusability	3/5
Simplicity	5/5
Performance	2/5
Resource sharing	1/5
Developer experience	4/5

Table 3.1: Evaluation of link-based composition

3.2.2 Composition via Iframes

An inline frame (iframe) is an old yet still widely used technique in web development. An iframe is an inline HTML element that represents a nested browsing context, allowing one HTML page to be embedded within another [33]. Each embedded context has its own document and supports independent URL navigation [33]. Compared to link-based composition, iframes allow multiple pages to be combined into a single unified view while maintaining almost the same level of loose coupling and robustness [1]. To add an iframe, we simply utilize the `<iframe>` tag, similar to an anchor `<a>` tag.

```
<iframe src="https://example.com/mfe2"></iframe>
```

The iframe can be further restricted via the `sandbox` attribute as follows:

- `<iframe sandbox src="..."></iframe>` - prevents the execution of JavaScript and form submissions.
- `<iframe sandbox="allow-scripts" src="..."></iframe>` - prevents form submissions but allows JavaScript execution.
- `<iframe sandbox="allow-forms" src="..."></iframe>` - prevents JavaScript execution but allows form submissions [1].

Its behavior and appearance can be customized via different attributes [33], and it can communicate with the host page through the `window.postMessage()` method.

Advantages

The biggest advantage of iframes is their excellent robustness and isolation, ensuring that styling and scripts do not interfere with each other. Iframes are also very easy to set up and work with. They are fully supported across all browsers and bring a lot of built-in security features [2][8][1].

Disadvantages

However, the main benefit is also the main drawback. It is impossible to share common dependencies across different iframes, leading to larger file sizes and longer download times [3]. It is also difficult to integrate them with each other, making communication, routing, and history management more complicated [8]. The host application must know the height of the iframe in advance to prevent scrollbars and whitespace, which can be fairly complicated in responsive websites [1][2]. Every iframe creates a new browsing context, which requires a lot of memory and CPU usage. Numerous iframes on the same page can significantly worsen application performance [2]. Lastly, they perform poorly in terms of search engine optimization (SEO) and accessibility [2].

Suitability

Despite the relatively long list of disadvantages, iframes can still be a valid choice for some projects. Iframes shine when there is not much communication between micro-frontends, and the encapsulation of our system using a sandbox for each micro-frontend is crucial. The best use cases for iframes are in desktop, B2B, and internal applications. However, other approaches should be preferred if performance, SEO, accessibility, or responsiveness are crucial factors [2][1]. Our evaluation of this approach can be found in table 3.2.

Aspect	**Score**
Extensibility	4/5
Reusability	3/5
Simplicity	4/5
Performance	1/5
Resource sharing	2/5
Developer experience	4/5

Table 3.2: Evaluation of composition via iframes

3.2.3 Composition via Ajax

Asynchronous JavaScript and XML (AJAX) is a technique that enables fetching content from a server through asynchronous HTTP requests. It then uses the retrieved content to update parts of the website without requiring a full-page reload [34]. To use AJAX as an approach for microfrontends, each team must first expose their microfrontend on a specific endpoint. Next, we create a corresponding empty element in the host application and specify the URL in a data attribute from which the content should be downloaded. Finally, JavaScript code is needed to locate the element, retrieve the URL, fetch the content from the endpoint, and append it to the DOM [2]. However, this approach introduces additional challenges, such as CSS conflicts in cases where multiple microfrontends use the same class names, leading to unintended overrides. To avoid this, all CSS selectors should be prefixed with the microfrontend name. Alternatively, tools such as SASS, CSS Modules, or PostCSS [35] can handle this for us. A similar issue can occur with scripts; to avoid it, we can wrap the scripts within Immediately Invoked Function Expressions (IIFE) to limit the scope to the anonymous function and prefix global variables [2]. The composition can then be handled as follows.

```
<div id="mfe2" data-url="https://example.com/mfe2"></div>
```

```
<script>
  const element = document.getElementById("mfe2");
  const url = element.getAttribute("data-url");

  window
    .fetch(url)
    .then(res => res.text())
    .then(html => element.innerHTML = html);
</script>
```

Since all the microfrontends are included in the same DOM, they are no longer treated as separate pages, as was the case with iframes. This eliminates the SEO and accessibility issues associated with iframe-based composition. There are no longer issues with responsiveness, as the microfrontends will be loaded as standard HTML elements, which can be styled as needed. This approach also provides greater flexibility for error handling; if the fetch request fails, for example, a direct link to the standalone page can be provided [2]. This approach also reduces initial load time since only essential content is loaded, while other microfrontends are loaded later asynchronously.

Disadvantages

One obvious disadvantage is the delay before the page is fully loaded. Since microfrontends must be downloaded, parts of the page may appear a bit later, which can worsen the user experience. Another significant issue is the lack of isolation between microfrontends, which can result in conflicts and overwriting between them. Lastly, there are no lifecycle methods built-in for the scripts, and these must be implemented from scratch [2].

Suitability

This approach is well-established, robust, and easy to implement. It is particularly well-suited for websites where markup is primarily generated on the server side. However, for pages that require a higher degree of interactivity or rely heavily on managing local state, other client-side approaches may be more suitable [2]. Our evaluation of this approach can be found in table 3.3.

3.2.4 Server-side Composition

As Geers explains: “Server-side composition is typically performed by a service that sits between the browser and the actual application servers.” After a user requests a page, the initial HTML is generated on the server. The ‘index.html‘ file contains

Aspect	Score
Extensibility	4/5
Reusability	4/5
Simplicity	3/5
Performance	3/5
Resource sharing	3/5
Developer experience	3/5

Table 3.3: Evaluation of composition via Ajax

common page elements and uses server-side includes (SSI) directives for places where microfrontends should be plugged in [8]. An example page would look as follows:

```
<html>
  <head>
    <meta charset="utf-8">
    <title>Example page</title>
  </head>
  <body>
    <p>Common element</p>
    <!--# include virtual="/mfe2" -->
  </body>
</html>
```

We would serve this file using a web server such as Nginx, which replaces directives with the contents of the referenced URL—microfrontends in our case—before passing the markup to the client. The configuration could look as follows [8]:

```
# defines a group of servers that handle requests
upstream mfe1 {
  server team_mfe1:8081;
}
upstream mfe2 {
  server team_mfe2:8082;
}
server {
  listen 8080;
  ssi on; # enables server-side include feature
  index index.html; # all locations should render through index.html

  location /mfe2 {
```

```
    proxy_pass http://team_mfe2;
  }
  location / {
    proxy_pass http://team_mfe1;
  }
}
```

Microfrontends can be deployed either as static assets or as dynamic assets, where an application server generates the templates for every user's request [1], with each having its own deployment pipeline. Communication is typically handled via APIs since the page must reload on all significant user actions. However, if some communication between microfrontends must happen on the client side, Mezzalira [1] suggests adding client-side JavaScript and using event emitters or custom events, keeping the microfrontends loosely coupled.

If possible, a CDN layer should be placed in front of the application server to cache as many requests as possible and reduce server load. Several frameworks, such as Podium, Mosaic, Puzzle.js, and Ara Framework, further simplify the implementation.

Advantages

Server-side composition is a proven, robust, and reliable technique. It offers excellent first-load performance, as the page is pre-assembled on the server, positively impacting search engine ranking. Maintenance is straightforward, and interactive functionality can be added via client-side JavaScript. It is also well-tested and well-documented [2][1].

Disadvantages

For larger server-rendered pages, browsers may spend considerable time downloading markup rather than prioritizing essential assets. Additionally, technical isolation is limited, requiring the use of prefixes and namespacing to prevent conflicts. The local development experience is also more complex [2]. Furthermore, if web pages are not highly cacheable but are instead personalized per user request, scalability issues may arise due to excessive server load [6].

Suitability

This approach is ideal for pages that prioritize performance and search engine ranking, as it remains reliable and fully functional even without JavaScript [2]. This architecture is recommended for B2B applications with common modules reused across multiple

views and teams consisting of full-stack or backend developers. However, it may not be optimal for pages requiring a high level of interactivity [1]. Our evaluation of this approach can be found in table 3.4.

Aspect	**Score**
Extensibility	4/5
Reusability	4/5
Simplicity	2/5
Performance	4/5
Resource sharing	4/5
Developer experience	3/5

Table 3.4: Evaluation of server-side composition

3.2.5 Edge-side Composition

Edge-side composition is typically performed at the CDN level. As Mezzalira [1] explains it: "Edge-Side Includes (ESI) is a markup language used for assembling different HTML fragments into an HTML page and serving the final result to a client. CDN providers such as Akamai and proxy servers like Varnish, Squid, and Mongrel all support ESI [2]." An edge-side composition solution is very similar to a server-side one; we swap the Nginx server with, for example, Varnish and use ESI directives instead of SSI. An edge-side include directive looks like the following:

```
<esi:include src="https://example.com/mfe2"
  alt="https://fallback.example.com/mfe2" />
```

If the fragment from the `src` URL fails to load, the content from the `alt` URL will be used instead [2]. After the markup language is interpreted, the result is a completely static HTML page renderable by a browser [1].

Advantages

Since we are composing the pages at the edge, response times are reduced as content is served closer to users. It also avoids the server-side problem of too many requests to servers, handling high loads more efficiently [1].

Disadvantages

The first drawback of this technique is that ESI is not implemented in the same way by each CDN provider or proxy server. Therefore, a multi-CDN strategy, as well as porting application code from one provider to another, could cause serious issues [6].

Another problem is that ESI cannot be used for dynamic pages. A potential solution to this problem could be adding client-side JavaScript, but this brings extra complexity [1]. Additionally, due to the poor adoption of this approach, the developer experience is not the best, and it lacks documentation and tools compared to other solutions [1].

Suitability

This approach is typically only used for large static websites that are not personalized for each user. According to Mezzalira [1], the IKEA catalog was implemented in some countries using ESI. Our evaluation of this approach can be found in Table 3.5.

Aspect	Score
Extensibility	4/5
Reusability	4/5
Simplicity	2/5
Performance	5/5
Resource sharing	3/5
Developer experience	1/5

Table 3.5: Evaluation of edge-side composition

3.2.6 Composition via Module Federation

This is a fairly new approach, made possible by the release of Webpack 5 [36]. Module Federation is Webpack's native plugin, allowing chunks of JavaScript code to load synchronously or asynchronously [1]. As Mezzalira [1] explains, a Module Federation application consists of two parts:

- The host – Represents the main application that loads microfrontends and libraries. The Webpack configuration for the host could look as follows:

```
new ModuleFederationPlugin({
  name: "host",
  remotes: {
    mfe1: "https://example.com/mfe1/bundle.js",
    mfe2: "https://example.com/mfe2/bundle.js",
  },
});
```

- The remote - Represents the microfrontend or library that will be loaded inside a host at runtime. The Webpack configuration for the remote could look as follows:

```
new ModuleFederationPlugin({
  name: "mfe1",
  filename: "bundle.js",
  shared: ["react", "react-dom"],
});
```

The composition takes place at runtime, which can either be on the client side, with the application shell loading different microfrontends, or on the server side, with server-side rendering at the origin [1]. With Module Federation, it is very easy to expose different microfrontends. It also supports sharing external libraries across multiple microfrontends, ensuring they are loaded only once. If some microfrontends use different versions of the same libraries, this is handled automatically by wrapping them in different scopes, preventing conflicts [1]. It also supports bidirectional code sharing across microfrontends, but this should be avoided as it goes against microfrontend principles. For communication, we could use event emitters or custom events.

Advantages

The biggest advantage of this approach is that it comes with a lot of tooling, solving most of the microfrontend challenges, such as lazy-loading, library sharing (even with different versions), microfrontend loading, and more. It supports both client and server-side rendering. Additionally, it benefits from the Webpack ecosystem, as other plugins can be used to customize the bundles even further. It provides a very high level of abstraction, making the developer experience almost as smooth as in a monolithic application.

Disadvantages

The main disadvantage of this approach is that it requires Webpack expertise. Additionally, the simplicity of code sharing across projects can lead to a very complicated architecture if the team is not disciplined or skilled enough [1].

Suitability

This approach is suitable for most types of projects, as it supports both server- and client-side rendering. However, it is especially well-suited for environments where Webpack is the standard within the organization [36]. Our evaluation of this approach can be found in Table 3.6.

Aspect	Score
Extensibility	4/5
Reusability	4/5
Simplicity	4/5
Performance	5/5
Resource sharing	4/5
Developer experience	5/5

Table 3.6: Evaluation of composition via Module Federation

3.2.7 Composition via Web Components

A relatively new approach that is beginning to emerge, thanks to new HTML, JavaScript, and CSS standards, is composition via Web Components. This approach is somewhat of a variation of composition via Ajax. As Web Components were already described in detail in the previous section, we will only focus on the implementation part.

First, we need to create a custom element, which will represent our microfrontend by extending the `HTMLElement` class and attaching a Shadow DOM to it. To keep things simple, we will not utilize HTML templates.

```
class MFE2 extends HTMLElement {
  constructor() {
    super();
    this.attachShadow({ mode: 'open' });
  }

  connectedCallback() {
    let message = this.getAttribute("message");
    this.render(message);
  }

  render(message) {
    this.shadowRoot.innerHTML = `
      <style>p { color: red; }</style>
      <p>${message}</p>
    `;
  }
}
```

We can utilize the `getAttribute(name)` method inside the custom element to obtain

attribute values provided by the parent, which can further customize the appearance and behavior of the element. Afterwards, we need to register the element.

```
customElements.define('mfe-2', MFE2);
```

Finally, we can use it anywhere, just like a standard HTML element.

```
<mfe-2 message="Hello World"></mfe-2>
```

For communication, we typically utilize `CustomEvents`, which were also discussed in the previous chapter ??.

Advantages

Web Components are now a widely implemented web standard that offers strong isolation managed by the browser when we use the Shadow DOM. Web Components provide many built-in lifecycle methods and can be used across different frameworks and libraries, such as Angular and React, making them even easier to implement [2]. They offer a great level of reusability and flexibility.

Disadvantages

One issue with Web Components is that they are not fully supported in all older browsers. Polyfilling can extend support for custom elements, but integrating the Shadow DOM is notably more challenging, and polyfills significantly increase the bundle size. Additionally, Web Components lack built-in state management mechanisms. Finally, handling SEO and accessibility can also be challenging [2][1].

Suitability

Web Components are an excellent choice for multitenant environments and are well-suited for building interactive, app-like applications. However, for applications that prioritize SEO or require compatibility with legacy browsers, Web Components may not be the most suitable option [2][1]. Our evaluation of this approach can be found in table 3.7.

3.2.8 Decision-Making

When choosing a composition approach for the implementation of a prototypical microfrontend application, which will be described in detail in the next chapter 4, we had to consider that this thesis focuses on enterprise-level application development. These applications are typically large-scale, highly modularized systems that can be easily

Aspect	Score
Extensibility	4/5
Reusability	5/5
Simplicity	4/5
Performance	4/5
Resource sharing	3/5
Developer experience	4/5

Table 3.7: Evaluation of composition via Web-components

scaled. Maintainability is another critical aspect, along with performance. Special emphasis must be placed on security, performance, and reliability. The goal is to rely on well-established, industry-standard technologies, rather than experimenting with new ones.

These requirements best fit server-side, Web Components, and Module Federation composition approaches. Server-side rendering is a traditional, well-established approach that has been in use long before microfrontends existed, with many resources and studies surrounding it. However, it does not excel at highly interactive applications. Module Federation is a relatively new technique, but it has already been widely adopted, with a lot of resources available on it compared to other approaches. But it does not offer much room for research and experimentation. Lastly, Web Components, although they have also been fairly adopted, lack as many studies. They are fully supported by Angular, a standard technology in the enterprise world. Web Components offer a great level of reusability, scalability, and performance. Finally, they are perfect for highly interactive applications, which is exactly what we need for our prototypical application. Therefore, for the implementation of the application, we have decided to go with a Web Components-based approach.

3.2.9 Summary

As we can see, all of the approaches have their set of advantages and disadvantages. We have realized that there is no such thing as the best architecture, only the lesser of the worse options, based on the project specifications. Each approach can be a good choice for certain projects. The table 3.8 combines all tables into a single, easy-to-read one, allowing for direct comparisons of all the mentioned approaches. The names of the approaches have been shortened so that the table fits well on the page.

Aspect	**Link**	**Iframes**	**Ajax**	**Server**	**Edge**	**MF**	**WC**
Extensibility	4/5	4/5	4/5	4/5	4/5	4/5	4/5
Reusability	3/5	3/5	4/5	4/5	4/5	4/5	5/5
Simplicity	5/5	4/5	3/5	2/5	2/5	4/5	4/5
Performance	2/5	1/5	3/5	4/5	5/5	5/5	4/5
Resource sharing	1/5	2/5	3/5	4/5	3/5	4/5	3/5
Developer Experience	4/5	4/5	3/5	3/5	1/5	5/5	4/5

Table 3.8: Comparison of different composition approaches

Chapter 4

Design

This chapter describes the design considerations essential for the implementation of the resulting prototypical microfrontends application. It begins with a brief introduction to the application and its purpose. Subsequently, it examines its functional and non-functional requirements, followed by a dedicated section explaining the system architecture. Next, the technologies for implementation are listed. Finally, graphical user interface mockups are presented and explained.

4.1 Application Introduction

One of the requirements for the application was to focus on the enterprise landscape. The application should be logically divisible into independent business concerns, striking a balance where it is not overly simplistic for a microfrontends architecture to lose its relevance, yet not overly complex to develop within the boundaries of the thesis. One of the well-known examples that combines these criteria is a project management tool. However, a standard project management tool is quite large, with many features. Therefore, we will implement only its core functionality, sufficient for a PoC application. At its very core, its main purpose is to manage project users and their tasks, which will be our main focus. It will offer functionality for creating and managing users, managing tasks, linking them to users, and presenting such information in an easily comprehensible manner. These functionalities will be discussed in more detail in the next section.

4.2 Application Requirements

This section presents functional and non-functional requirements for the application, which will be categorized by priority as follows:

- (M) Must: Crucial for the system's operation.

- (S) Should: Highly recommended, though not mandatory.
- (C) Could: Optional for implementation.

4.2.1 Functional Requirements

Here is a comprehensive list of all functional requirements for the application.

User Management

For simplicity, we will not implement user registration or logins. The user roles will also be for informational purposes only, as every user will have full access to all functionalities.

- Users can create, update, and delete other users (M).
- Users are displayed in a table view (M).
- Users can set and update the following attributes for a user: name, email, phone number, role, status, bio (M).
- Users can be filtered by: their roles (S).

Task Management

A similar approach applies to tasks, everyone will be able to manage anyone's tasks.

- Users can create, update, and delete tasks (M).
- Tasks are displayed on a Kanban board (M).
- Users can set and update the following task attributes: title, status, priority, tag, due date, and description (M).
- Users can be linked to tasks as assignees (M).

Dashboard

- A new users widget are displayed on the dashboard (M).
- A new tasks widget are be displayed on the dashboard (M).
- The widgets communicate with each other in some way (M).
- The dashboard displays a monthly user count graph (C).
- The dashboard displays a monthly task completion graph (C).

Settings

- Users can switch between light and dark themes (C).
- Users can switch between Slovak and English languages (C).

4.2.2 Non-functional Requirements

Here is a comprehensive list of all non-functional requirements for the application.

- The application is divided into several microfrontends (M).
- Each microfrontend is isolated from the others to prevent cascading failures (M).
- The application is easily scalable by adding new microfrontends (M).
- The application is easy to use and intuitive (S).
- The microfrontends are easily customizable (S).

4.3 System Architecture

In this section, we explore the system architecture of the application, which adopts a microfrontend architecture to separate different business domains into distinct, independently developed, and deployed microfrontends. We will present the various microfrontends and other components that make up the system, explaining the rationale behind these segmentation decisions. Figure 4.1 illustrates this architecture through a UML component diagram.

Figure 4.1: Component diagram of the application architecture

4.3.1 Application Shell

The application shell is the core of the application; it functions as an orchestrator for all microfrontends. Based on the current route, it loads and renders the appropriate microfrontends. It handles all global functionality, such as routing, theme settings, and language switching, in one place for the application. It passes any necessary data down to the microfrontends, such as the current language (English or Slovak) or customization options. Common elements, such as navigation and settings, are also located here. Additionally, it renders the dashboard page by combining multiple microfrontends into a single unified view.

The reasoning behind this is quite clear — we wanted to keep all common elements in one place and handle global functionality centrally in a single part of the application. This greatly reduces code redundancy and improves maintainability. The application shell only needs to know the URLs where the microfrontends are hosted and their HTML element names and attributes. Other than that, it can be developed and deployed independently.

4.3.2 User Microfrontend

This microfrontend is primarily used for user management functionality within the application. It handles user management through CRUD operations (Create, Read, Update, Delete) and displays users in a table format. It is a standalone page within the application, which should be rendered on its own in the application shell. It can receive multiple attributes. The first one is the `language`, which the microfrontend should use, by default English. The second one is the `theme`, either light or dark. The last one is a boolean attribute: `compact`, which defaults to false. If this attribute is set to true, the microfrontend switches to compact mode, displaying only a simple list of new users and monthly users graph for dashboard purposes, allowing it to be displayed alongside other microfrontends. Clicking on a user in the list selects them, and clicking again deselects them. It also triggers an event to notify other microfrontends about this selection. Additionally, it listens for events related to task selection or deselection. In such cases, it only displays users assigned to the selected task.

By following this approach, the user management microfrontend remains completely isolated from the rest of the system. It is easily reusable, customizable, and serves a single business domain. The only information it needs to function correctly is the names of the events it should listen to.

4.3.3 Task Microfrontend

This microfrontend is primarily used for task management. Similar to the previous microfrontend, it handles task management through CRUD operations (Create, Read, Update, Delete) and displays tasks in a Kanban board. It is also a standalone page within the application, which should be rendered on its own in the application shell. It can receive the same attributes as the user management microfrontend. However, in compact mode, it displays only a list of new tasks and a task completion graph. Clicking on a task selects or deselects it and notifies other microfrontends within the same view about the selection. Additionally, it listens for user selection or deselection events from other microfrontends. In such cases, it filters and displays only the tasks where the selected user is an assignee.

The reasoning behind this is the same as in the case of the user management microfrontend.

4.3.4 Backend

n a true microfrontend project, each microfrontend would ideally have its own microservice and database. However, due to the limitations of this thesis and the extensive research already available on microservices and their implementation, we will focus primarily on the frontend side. For the backend, we will use a simple, lightweight monolithic architecture.

4.4 Tech Stack

This section outlines the technologies used in the implementation of the resulting application.

Angular

The primary framework for the application development will be Angular 18, the latest version of Angular available at the time of writing. Angular is a powerful, platform-agnostic web development framework created by Google that enables developers to build scalable, maintainable, and performant single-page applications (SPAs). In this project, Angular will be used to develop both the application shell and the microfrontends. The choice of Angular stems from its wide adoption in enterprise applications and built-in support for web components.

TypeScript

TypeScript will be the primary programming language for the project, as it is the standard language used in Angular development. TypeScript is a superset of JavaScript that adds static types, enabling developers to catch errors at compile time rather than at runtime. This helps reduce bugs and makes the code more reliable and easier to maintain. The additional type safety and tooling support offered by TypeScript make it a popular choice in the enterprise landscape, and this is one of the key reasons why it was chosen for the project.

Web Components

Web Components will be leveraged in this project to ensure that each microfrontend operates independently and can be integrated seamlessly into the application shell. In this project, each microfrontend will be exposed as a custom element. To avoid CSS conflicts and ensure style encapsulation, the shadow DOM will be used in each microfrontend.

Custom Events

To facilitate communication between the various microfrontends and the application shell, standard browser supported custom events will be utilized. Custom events provide a lightweight and efficient way to send and receive messages between different parts of the application, ensuring that microfrontends remain decoupled but can still share essential data when needed. This event-driven approach will serve as the primary method for cross-microfrontend communication, ensuring a flexible and scalable architecture.

Node.js

For the backend, we will use Node.js, a server-side JavaScript runtime environment built on an asynchronous, event-driven architecture, making it an efficient solution for building networked applications, such as web servers or APIs. In combination with Express.js, a flexible framework for Node.js, which provides a set of features and utilities for handling routing, requests, middleware, and more, this setup allows us to quickly establish the backend and gives us more time to focus on frontend development.

4.5 Graphical User Interface

In this section, we will present and describe the wireframes of the application. These wireframes illustrate the layout and structure of the user interface across different

parts of the system, providing a visual representation of how users will interact with the application. Each wireframe focuses on a specific microfrontend or application shell, showcasing its core functionality and design elements.

Application Shell

Figure 4.2: Wireframe of the application shell interface

As shown in the figure 4.2, the application shell consists of a side panel with a logo and navigation links for each microfrontend and a dashboard page. At the bottom of the side panel is a button to open the settings modal, which contains radio buttons for switching the language and application theme. The main content area, next to the side panel, is where all pages will be rendered. This could be either a single microfrontend or the dashboard page.

User Microfrontend

The user microfrontend interface 4.3 consists of a table where each row represents a user, displaying key details such as name, email, phone, role, and status. The last column of the table is dedicated to an action button, which opens a dropdown menu with options to view, edit, or delete a user. Upon selecting any of these actions, a modal window appears, allowing the user to execute the desired operation. Directly above the table is a set of tabs for quick filtering of users based on their roles (e.g., admin, developer, tester, etc.). At the very top, the topbar includes the page title, a brief subtitle, and a button to add a new user. Clicking this button opens a modal for user creation.

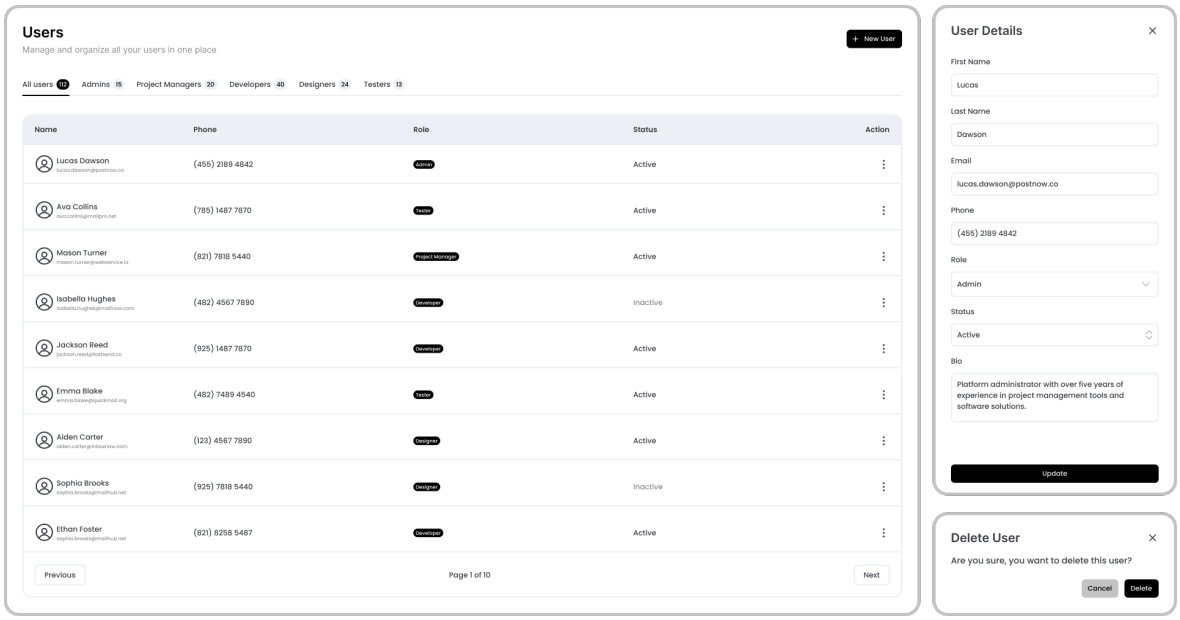

Figure 4.3: Wireframe of the user microfrontend interface

Task Microfrontend

The task microfrontend 4.4 is slightly different from the other sections, as its main component is a kanban board that organizes tasks into various stages, such as “Backlog”, “In-Progress”, “In-Review” and “Done”. Each task is represented by a card displaying essential details such as the title, tag, assignees, and more. In the upper-right corner of each task card, there is a three-dot button that opens a dropdown menu with options to view, edit, or delete the task. Upon selecting any of these actions, a modal window appears, allowing the user to execute the desired operation. Each stage on the kanban board includes a button for creating new tasks directly within that stage. At the top of the page is a topbar containing the page title, a brief subtitle, and a button to add a new task. Clicking this button opens a modal designed for task creation.

Dashboard

The dashboard 4.5 is a combination of the user microfrontend and task microfrontend, both in compact mode, along with application shell elements. At the top of the page is a topbar, which is located in the application shell codebase. Underneath it is the user microfrontend in compact mode, displaying the monthly users graph and the new users widget. At the bottom is the task microfrontend, also in compact mode, displaying the task completion graph and the new tasks widget. These two microfrontends communicate and interact with each other, as already described in the “System Architecture” section.

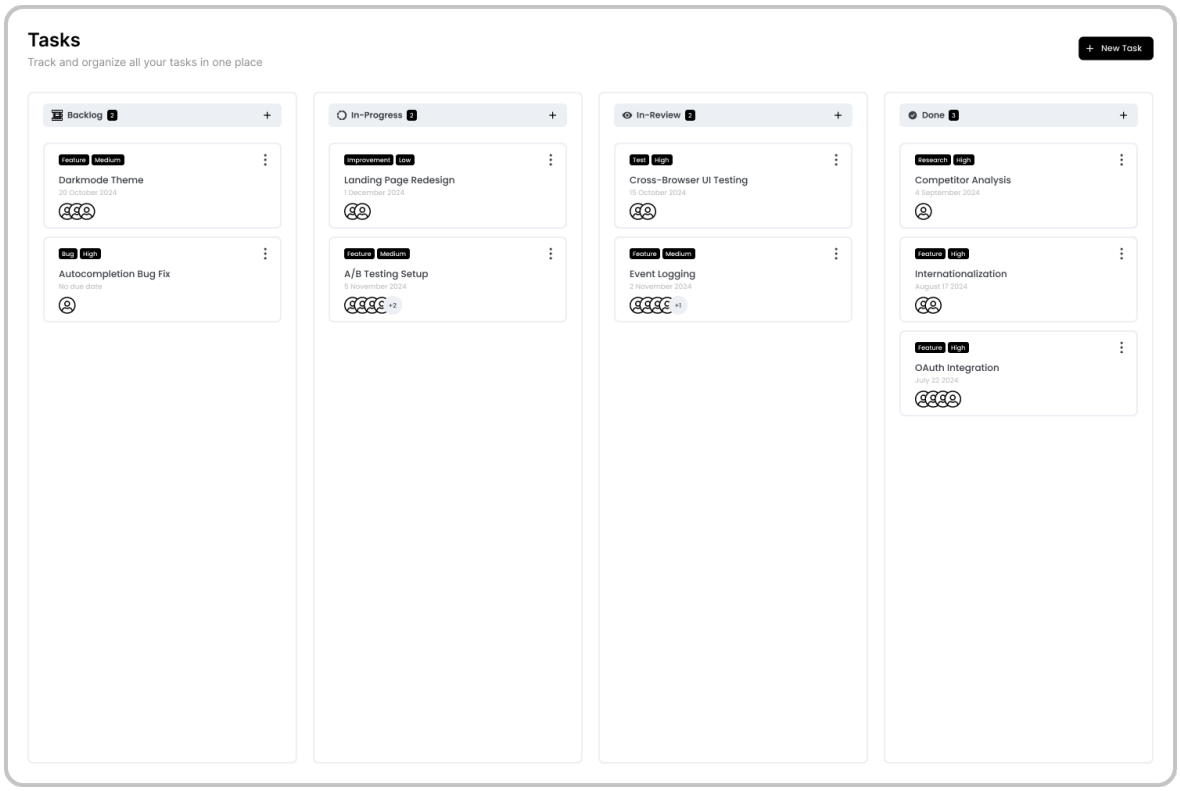

Figure 4.4: Wireframe of the task microfrontend interface

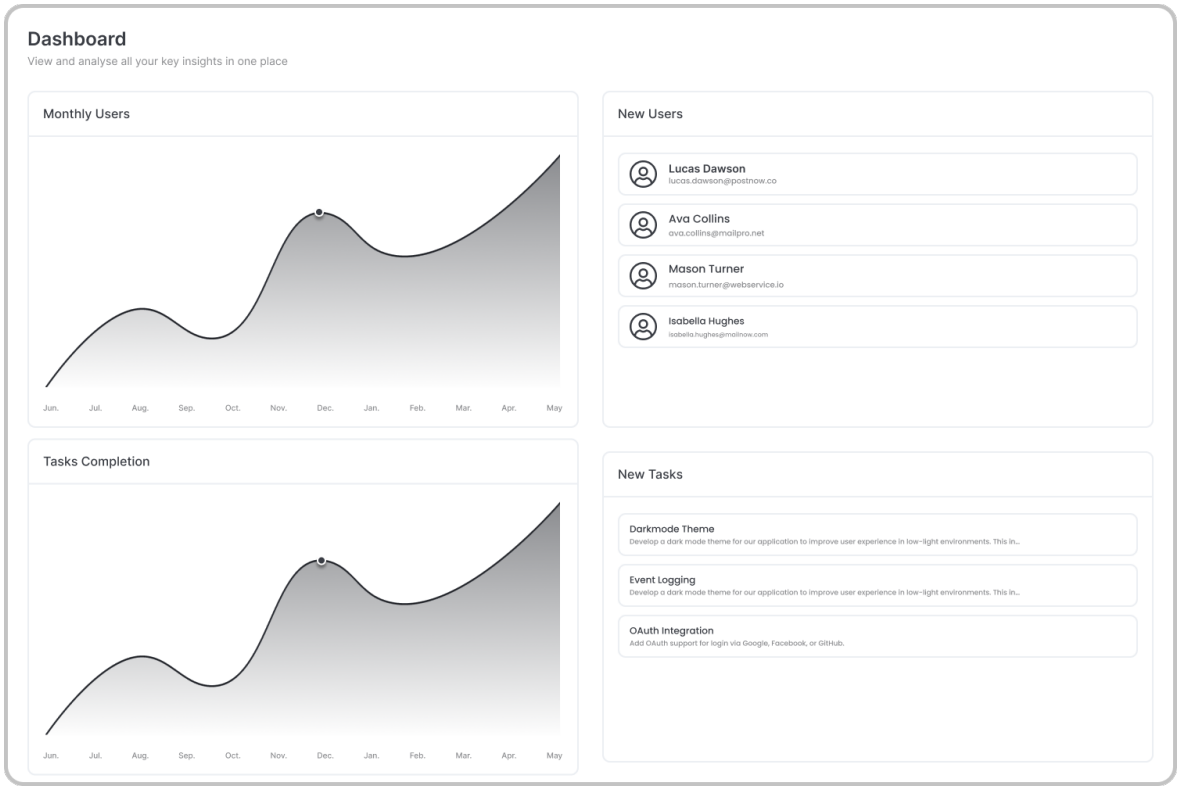

Figure 4.5: Wireframe of the dashboard interface

Chapter 5

Implementation

In this chapter, we will outline the implementation of a prototypical microfrontends-based project management application using Web Components and Angular. We will discuss the challenges encountered during development and the strategies used to address them. The chapter will cover an overall implementation overview, in-app communication and composition, routing and styling.

5.1 Overview

The application was developed using Angular 18 and consists of three separate Angular projects. The first one is the `application-shell`, which acts as a container for all microfrontends. The second one is `user-management`, representing the user microfrontend, and the last one is `task-management`, representing the task microfrontend.

All these projects were generated under the same Angular workspace. This was done purely for practical reasons, as there are no distinct teams working on the projects. In a real-world application, each microfrontend should be developed as a separate Angular project. The workspace was generated in the standard way using the following command.

```
ng new project-management-tool --create-application=false
```

Afterward, the application-shell project was generated using the standard method.

```
ng generate application application-shell
```

After generating the application, Bootstrap and `@ng-bootstrap/ng-bootstrap` were installed and configured in the standard way, along with `@ngx-translate`, a library for internationalization support. Interfaces were then designed using placeholder components for microfrontends. Support for theme switching (light/dark) and language

switching (Slovak/English) was added, with preferences saved in local storage. The `application-shell` was developed as a standard Angular application.

Microfrontends were generated in the same way but with the use of the –prefix option, such as following.

```
ng generate application user-management --prefix=user
```

The development of microfrontends followed a similar approach to the `application-shell`, with one key difference: the way the application is bootstrapped. Depending on the environment, the bootstrapping process varies. The microfrontends were then built and statically served using http-server package, each on a different port via the command line:

```
npx http-server dist/user-management/browser -p 4201
```

To avoid repeatedly typing these commands, they were added as script commands in `package.json`. The composition and loading of microfrontends will be further explained in the next section.

The microfrontends communicate with a backend, which is a standard Node.js server with Express.js. Each microfrontend has been assigned its own URL prefix, such as `/users` for the user microfrontend and `/tasks` for the task microfrontend. The microfrontends interact with the backend using Angular `HttpClient` for CRUD operations. We are not using any database; instead, data is stored only at runtime. In a real-world application, each microfrontend requiring a backend should ideally have its own microservice and dedicated database. However, due to the scope of this thesis and the focus on the frontend aspects of microfrontends, we chose a simplified approach to avoid unnecessary complexity.

5.2 Composition

For the application composition to work correctly, we had to utilize a couple of special techniques. First, we had to modify how the microfrontends would be built. There are two types of environments in which the microfrontends can operate. The first one is the local development environment, in which the microfrontend is built as a standard Angular application for easier debugging and development. The second one is the embedded environment, in which the microfrontend must be built as a custom element.

To build an Angular application as a custom element, we used the following piece of code.

```
const app = await createApplication(appConfig);
const customElement = createCustomElement(EntryComponent, {
  injector: app.injector,
});
customElements.define(environment.customElementName, customElement);
```

Instead of specifying the `AppComponent` as the component we want to build, we create a special component called `EntryComponent`. This component handles all inputs from the `application-shell` and renders the `AppComponent`. The `EntryComponent`, in the case of a microfrontend with no inputs, could look like the following.

```
@Component({
  selector: 'user-entry',
  standalone: true,
  imports: [AppComponent],
  template: '<user-root></user-root>',
  styleUrl: '../../../styles.scss',
})
export class EntryComponent {}
```

However, when we build the application this way, we end up with two JavaScript files (`polyfills.js`, `main.js`) and a CSS file (`style.css`). Multiple files complicate the loading of the microfrontends in the `application-shell`. To avoid this, we use Webpack to bundle the scripts and styles into a single file. Finally, we statically serve this file for the `application-shell`, as explained in the previous section.

Now, we need to look into how microfrontends are loaded in the `application-shell`. When a user navigates to a microfrontend route, the `LoadMicrofrontendGuard` ensures that the required JavaScript bundle is loaded before route activation. It first extracts the `bundleUrl` from the route data and then uses the `MicrofrontendRegistryService` to load the microfrontend. The service first checks if the microfrontend is already loaded; if not, it injects a script tag into the document with the provided `bundleUrl` to load it. In the case of a unified microfrontends view, we do not use the guard. Instead, we directly call the registry service for each microfrontend. If a microfrontend fails to load, we do not render it and simply move to the next one.

5.3 Communication

There are two types of intra-application communication occurring in our application.

Applicaition-Shell to Microfrontend

The first type of communication is from the `application-shell` down to a microfrontend. This occurs when we need to pass attributes to the microfrontend, such as the current language or whether it should be rendered in compact mode. It also happens when an attribute changes to a new value and the microfrontend needs to be informed about it. Since microfrontends are built as custom elements, we can pass any number of attributes as needed. However, proper handling must be implemented in the microfrontend. Therefore, the corresponding teams must define a contract beforehand, specifying which attributes can be passed between them. To pass an attribute, we simply specify it in the HTML as follows.

```
<user-management compact='true'></user-management>
```

In the microfrontend's entry component, we would then write the following.

```
@Input() compact: boolean = false;
```

For attributes that can change over time, such as language, we can create a directive to avoid repeatedly writing subscriptions to observables for each microfrontend. The language directive is defined in the shell like this:

```
@Directive({
  standalone: true,
  selector: '[microfrontendLanguage]',
})
export class MicrofrontendLanguageDirective implements OnInit, OnDestroy {
  private destroy$ = new Subject<void>();

  constructor(
    private element: ElementRef,
    private translateService: TranslateService
  ) {}

  ngOnInit(): void {
    this.translateService.onLangChange
      .pipe(
        map((event) => event.lang),
        startWith(
          this.translateService.currentLang ?? this.translateService.defaultLan
        ),
        takeUntil(this.destroy$)
```

```
      )
      .subscribe((language) => {
        this.element.nativeElement.language = language;
      });
  }

  ngOnDestroy(): void {
    this.destroy$.next();
  }
}
```

And it is used on the microfrontend elements like this:

```
<user-management microfrontendLanguage></user-management>
```

It is important to note that for attributes which can change over time, we need to define an `onChange` listener in the microfrontend entry component, as shown below:

```
@Input() language?: 'en' | 'sk';

ngOnChanges(changes: SimpleChanges): void {
  if (changes['language'] && this.language) {
    this.translateService.use(this.language);
  }
}
```

Microfrontend-to-Microfrontend

The second type of communication primarily involves communication between microfrontends, but it can also be used to communicate from the shell to a microfrontend or vice versa. This type of communication is handled via browser Custom Events. In each microfrontend, we create an event service with methods to listen for and emit events, as shown below:

```
private emit(eventName: string, data: any) {
  const customEvent = new CustomEvent(eventName, {
    detail: data,
    bubbles: true,
    composed: true,
  });

  window.dispatchEvent(customEvent);
```

```
  }

  private on(eventName: string, callback: (data: any) => void) {
    const windowListener = (event: CustomEvent) => callback(event.detail);
    window.addEventListener(eventName, windowListener as EventListener);

    return () => {
      window.removeEventListener(eventName, windowListener as EventListener);
    };
  }
```

The microfrontend teams must define a contract beforehand, describing what types of events their microfrontend will listen to and emit, as well as what type of data will be passed through those events. We can then define those listeners and emitters in whichever components are needed.

5.4 Routing

Routing is completely handled in the `application-shell`, using the standard approach via `@angular/router`. When a route for a component inside the application shell is requested, we simply load the component in the standard way. If a route for a microfrontend is requested, we first check if the microfrontend can be loaded via a route guard. If it can, we then lazy-load the microfrontend by injecting a script tag with the provided `bundleUrl`, as already explained in the previous section. Each microfrontend that should be rendered as a separate page has its own route definition, which looks, for example, like following.

```
export const USER_MANAGEMENT_ROUTES: Routes = [
  {
    path: '**',
    canActivate: [LoadMicrofrontendGuard],
    component: UserManagementHostComponent,
    data: {
      bundleUrl: 'http://localhost:4201/bundle.js',
      compact: false,
    },
  },
];
```

And the host component would then look like the following.

```
@Component({
  selector: 'user-management-host',
  standalone: true,
  imports: [MicrofrontendLanguageDirective],
  template: `<user-management microfrontendLanguage></user-management>`,
  schemas: [CUSTOM_ELEMENTS_SCHEMA],
})
export class UserManagementHostComponent {}
```

In the case of multiple microfrontends on the same page, we define the page and the route in the `application-shell` like any other page and load the microfrontends directly using the `MicrofrontendRegistryService`.

In our case, we do not have a microfrontend with multiple pages. However, if that were the case, we would propagate the full route from the shell down to the microfrontend via an attribute. The microfrontend would then have its own router and handle the route internally. In the case of a route change triggered within the microfrontend (not the application-shell), we would propagate the new route to the shell, which would handle it as necessary, pass it back to the microfrontend, and only then would the route change in the microfrontend.

5.5 Styling

To keep the user interface consistent across the application-shell and microfrontends, we use Bootstrap for styling in each of them. This way, each part of the application looks the same style-wise, unless we modify the Bootstrap classes significantly. Another issue we had to solve is styling isolation, so that if we use the same class name in two microfrontends, they do not override each other. To avoid this, we utilize the Shadow DOM. This is very simple in Angular; we set the encapsulation to ViewEncapsulation in the microfrontend entry component, as shown below.

```
@Component({
  ...,
  styleUrl: '../../../styles.scss',
  encapsulation: ViewEncapsulation.ShadowDom,
})
export class EntryComponent implements {...}
```

However, for this to work properly with Bootstrap, we also had to change how Bootstrap is imported. Instead of importing Bootstrap in the styles section of `angular.json`,

we imported it directly in the global styles file. We then link this global styles file in the `styleUrls` property of the microfrontend entry component. And that was it—each microfrontend has had its own isolated, separate DOM tree since then.

Chapter 6

Evaluation Results

This chapter analyzes and evaluates the implemented prototypical application in terms of reusability, extensibility, resource sharing, and application state management, with each aspect discussed in its own section.

6.1 Reusability

Reusability refers to the ability of software components—in our case, microfrontends—to be used across multiple applications or within different parts of the same application with minimal modifications. Our application achieves a high degree of reusability due to three key factors.

First, it leverages Web Components, a browser standard that allows components to be reused in any environment or framework. Second, well-designed boundaries and domains for the microfrontends enable their reuse across different applications. For example, the user microfrontend can be used in almost any application that supports user roles, as user management is an essential part of most systems. Lastly, the microfrontends are already being reused within the application dashboard through the compact mode attribute.

However, our implementation also introduces a challenge to reusability, as microfrontends cannot be easily styled externally. This is due to two factors. First, they come with their own dependencies and do not share any with the parent application. Second, they utilize the Shadow DOM, which isolates their DOM tree, making it inaccessible from the outside.

6.2 Extensibility

Extensibility refers to the ability of a system to be enhanced with new functionality or modifications without requiring significant changes to existing components. Our

microfrontend architecture is designed with extensibility in mind.

For small modifications, changes typically affect only a single microfrontend due to the logical separation by domains. At most, new event handlers may need to be added to surrounding microfrontends. Compared to monolithic frontends, modifying a single microfrontend is significantly easier, as each has a smaller, more manageable codebase with little to no coupling.

For major changes, new functionality usually falls into its own domain and is added as a completely new microfrontend. Adding a new microfrontend is straightforward—since they are developed as standard Angular applications for most part and transformed into custom elements only at build time. Existing microfrontends remain unchanged, with only the application shell needing to register the new route and microfrontend.

However, one challenge with our current implementation is that each microfrontend comes with its own dependencies. A large number of microfrontends could lead to performance issues due to redundant dependencies. To address this, some form of dependency sharing would need to be implemented.

6.3 Resource Sharing

Resource sharing in our context refers to the ability of microfrontends to efficiently utilize and share common assets, dependencies, and services to minimize redundancy and improve performance. This is an area where our implementation faces the most challenges.

Although each microfrontend and the application shell use the same version of most dependencies, such as Bootstrap, each microfrontend brings its own version. This is a tradeoff we've accepted for the strong isolation provided by Web Components. Currently, our microfrontends do not share any assets besides translations, which are fetched from the backend at runtime.

In the event that we need to share other assets across microfrontends, we could implement a solution by setting an environment variable URL that points to a shared cloud storage location. This would allow all microfrontends to fetch assets from a centralized location. However generally, this area of our application requires further research and improvements to ensure optimal performance and efficient resource sharing.

6.4 Application State Management

Application state management refers to the synchronization of data across different parts of the application. In a microfrontend architecture, managing application state becomes more complex due to the independent nature of each microfrontend. In our application, there is not much state to manage, aside from the current language and theme. To handle these, we use a combination of local storage and attributes, which can be passed from the shell to the microfrontends. Both of these states are managed centrally in the application shell. User preferences are stored in local storage, and upon initialization or any change, they are passed as attributes down to the microfrontends.

For more complex state management, a more robust solution would need to be implemented to avoid overusing attributes and causing unnecessary re-renders of microfrontends.

Chapter 7

Conclusion

Provide a description outlining the purpose and content of this chapter, detailing the topics being discussed herein.

7.1 Implementation Results

- Presents the findings and outcomes from the implementation and analysis of microfrontend architectures.
- Cover key metrics, performance indicators, and notable observations to support the thesis's conclusions.

7.2 Practical Implications

Discuss the circumstances under which microfrontends are suitable and when they may not be the optimal solution.

7.3 Recommendations for Future Work

Outline potential areas for future research and improvement in microfrontend architectures.

[?]

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