5 Design

In this section, we provide a detailed overview of the design of our web application for assessing Systems Engineering (SE) competency, addressing the limitations and challenges identified in previous sections. We examine the System's Functional Architecture from the user's perspective, focusing on how individuals assess the application. Next, the section explains the survey paths available to the users: Role-based assessment, Task-based assessment, and Full comprehensive assessment. Following this, we shift to the admin perspective, detailing the preparatory steps required to configure the system before surveys can be conducted. This includes an in-depth discussion on data models that administrators must configure, ensuring the system is set up to capture role-specific and organization-specific competency requirements. We then present the complete SE competency assessment workflow, outlining how users interact with the system and what happens in the system while users complete their evaluations. The final section discusses the design of the survey questionnaires by explaining how they are structured to ensure accurate competency measurement and incorporating validated scientific approaches to improve assessment reliability.

5.1 System Functional Architecture: User Perspective: Performing the Assessment

The SE competency assessment web application is designed to evaluate the competency levels of Systems Engineers based on their roles and responsibilities within an organization. The system provides users multiple pathways to assess their competencies, ensuring flexibility and adaptability to diverse organizational structures and individual career trajectories. Figure 5-1 illustrates the functional overview of the system from the perspective of a user taking the survey. It depicts the core processes and interactions involved in competency assessment.

The SE competency assessment process begins when the user initiates the survey and selects one of three available pathways. In the Role-Based Competency Assessment, users select one or more roles from the predefined role clusters. The system determines the required competency levels for performing the selected roles. The user's responses are

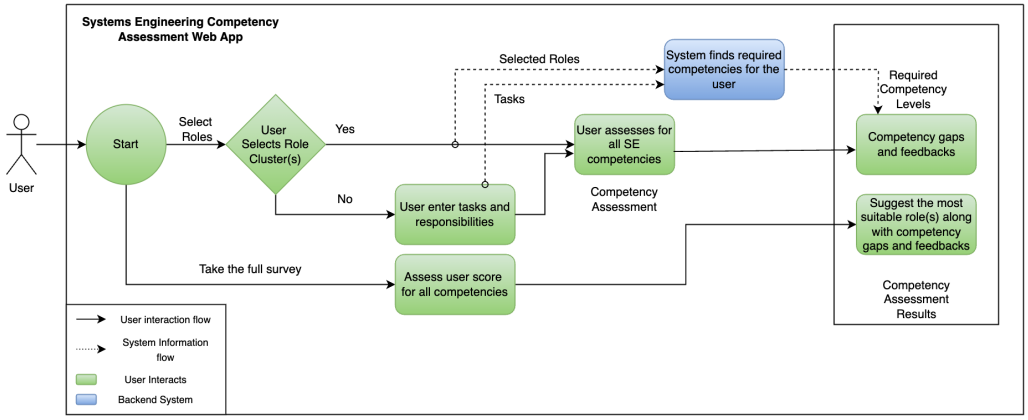

Figure 5-1: Functional Overview of the Competency Assessment System from User Perspective

then evaluated against these predefined requirements, allowing for a direct comparison of recorded competencies with those necessary for the selected role(s).

In the Task-Based Competency Assessment, users who cannot directly map their job role to the predefined role clusters provide details about their job tasks and responsibilities, categorized by their level of involvement (e.g., responsible for, supporting, or designing). The system then maps these tasks to relevant ISO processes using an intelligent inference mechanism, deriving the necessary competencies for performing these tasks, against which the user is assessed.

In the Full Competency Assessment, users comprehensively evaluate all competencies within the framework. Based on their survey responses, the system analyzes their competency profile and suggests the most suitable roles, identifying those that best align with their demonstrated competencies. The following sections provide a detailed explanation of each of these three assessment pathways.

5.1.1 Survey Paths and and their Logic

5.1.1.1 Role-Based Competency Assessment

In this pathway, users have the option to select one or more roles from a predefined set of 14 role clusters from the KÖNEMANN et al.'s methodology[KWA+22]. If a user's current role at work aligns with one or more of these predefined clusters, they can select the corresponding role(s) for competency assessment. The system determines the required com-

petencies for each role using the Role–Competency Matrix, which specifies the necessary competency levels for effectively performing a given role (refer Section 3.4).

For users selecting multiple roles, the system identifies the competency requirements necessary to perform the selected roles. This ensures that individuals who take on multiple responsibilities receive a comprehensive evaluation that accurately reflects their professional requirements.

5.1.1.2 Task-Based Competency Assessment

This survey pathway is for a user who cannot identify their role within the 14 predefined role clusters. These users can input their job tasks, responsibilities, and level of involvement. The involvement levels are categorized as *Not Applicable, Supporting, Responsible, or Designing*. Based on this input, an intelligent mechanism should be utilized to map the tasks to the relevant ISO processes.

Once the system identifies the ISO processes performed by the user, it utilizes them in combination with the Role-process matrix and the Process-competency matrix to derive the required competencies for performing this unknown role using the Role-Competency Matrix derivation explained in section 3.4.

This approach ensures that the competency assessment remains flexible and inclusive. It accommodates users from diverse organizational backgrounds where predefined role titles may not accurately reflect their actual responsibilities [DAR$^+$21] [INC23b]. Additionally, some organizations may use role names that differ entirely from the role cluster names defined in the system[SH22]. In such cases, the task-based assessment allows users to map their work responsibilities to competency requirements without relying on predefined role classifications. This ensures that the evaluation remains relevant and accurate, regardless of the specific terminology used within an organization.

5.1.1.3 Comprehensive Competency Assessment

In this survey path, the system can assess all competencies for users seeking a complete SE competency evaluation without requiring prior role selection. Users are evaluated across the entire set of 16 competencies defined in the system. Based on the assessment results, the system determines the user's best role(s) by comparing their competency profile with the Role-Competency matrix. This approach ensures that users receive role recommendations aligning with their demonstrated competencies. It also provides insights into potential roles that best match their skills and knowledge.

This assessment method is particularly valuable for organizations, as it helps assign roles to new employees or restructure teams based on individual competency profiles. Using this data-driven approach, organizations can make informed decisions about workforce planning and ensure employees are placed in roles where their skills are best used.

5.2 System Functional Architecture: Admin Perspective: Preparation for the Assessment

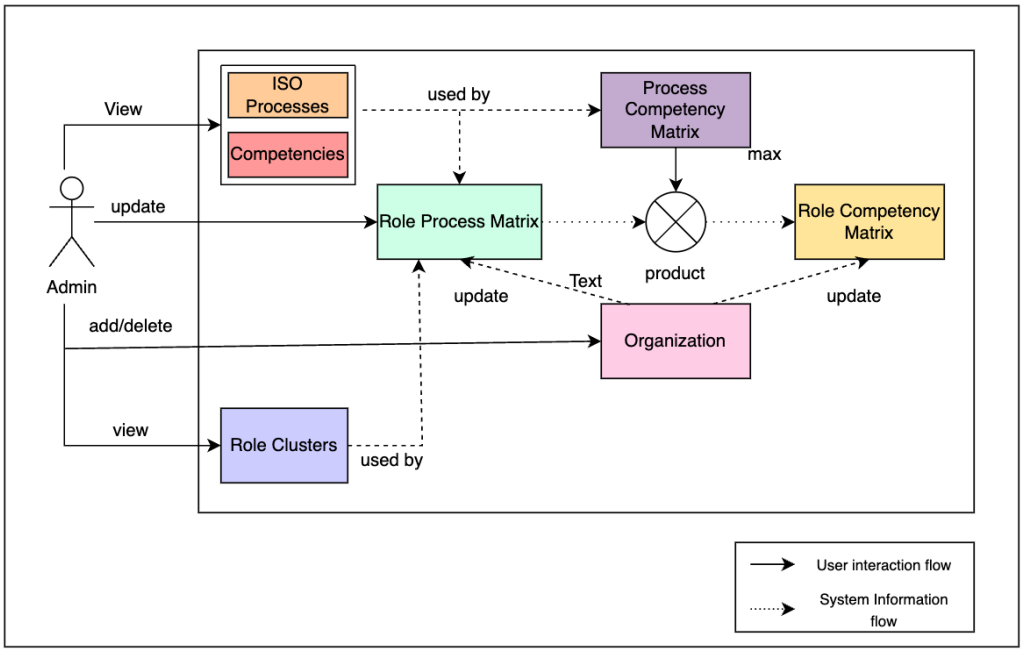

Figure 5-2: Functional Overview of the Competency Assessment System from Admin Perspective and Data Models

Figure 5-2 illustrates the high-level functional architecture of the competency assessment system from an administrative perspective. It highlights the system's key data models that administrators must set up to prepare it for effective SE competency evaluation.

The SE competency assessment app is designed to offer a structured and adaptable framework that allows administrators to manage and configure essential components. These include the Role-process matrix and the Process-competency matrix, which are derived from core foundational elements such as ISO processes, competencies, role clusters, and organizational configurations. Together, these components form the fundamental data

models for the SE competency assessment framework, enabling a standardized competency evaluation process in diverse roles and organizational contexts.

The system administrator configures and manages the components required for competency assessment, as illustrated in Figure 5-2. This includes defining ISO processes and competencies, which are the foundations for competency evaluation. These elements are then used to establish the Role-Process matrix and Process-Competency matrix, which are used to determine the competency requirements for different roles 3.4. Since the Role–Competency Matrix is conceptually derived from the Role–Process Matrix and the Process–Competency Matrix, any updates to these foundational matrices require recomputation of the Role Competency Matrix.

To support multiple organizations with various competency requirements, a corresponding Role–Process Matrix is defined for that organization whenever a new organization is introduced into the system. The administrator, in collaboration with the organizational representative, is responsible for configuring this matrix by defining the roles and ISO processes performed by the roles within the organization. This ensures that the competency assessment framework accurately reflects the organization's structure and job functions.

The system is designed to support evolving organizational needs. By structuring assessments around well-defined matrices from KÖNEMANN et al's framework[KWA+22], the system provides a standardized yet flexible approach to competency evaluation.

The following section discusses the data models in Figure 5-2. The administrator should configure these data models to prepare the system for SE competency evaluation. Additionally, we explain how these models are interconnected and designed to depend on each other to ensure a structured and consistent competency assessment framework.

5.2.1 Overview of Data Models

Figure 5-2 illustrates the key data models of the SE competency assessment system and their interdependencies. These models serve as the foundation for the SE competency evaluation and define the relationships between roles, processes, and competencies[KWA+22]. The administrator is crucial in managing and updating these elements to align the system with organizational structures and competency requirements. The administrator is responsible for configuring and refining these data models to ensure the assessment framework remains relevant and effective. In the following subsections, we describe each data model and its role in the competency assessment process.

ISO Processes and Competencies

Our framework for assessing SE competencies is built on a predefined set of ISO processes [Int23b] and SE competencies 3.2.2, which serve as a foundation for evaluating SE competencies within organizations.

- **ISO Processes** Data Model defines the standardized engineering processes organizations follow to ensure compliance with industry regulations and best practices [Int23b]. The administrator configures this model by adding the required ISO processes to the system. These processes form a fundamental part of the competency assessment framework, establishing the relationship between roles and required competencies.

  Since ISO processes are derived from established standards, they are considered static and are not expected to change frequently. Any modification to this model would require adjustments to the Role–Process Matrix and the Role–Competency Matrix to maintain consistency in competency evaluations. However, in the current design, modifications (such as removing a process from the system) to ISO processes are not supported, as they are assumed to remain stable. The administrator's role is limited to viewing all ISO processes within the system, ensuring transparency in the competency framework.

  Future system enhancements could introduce flexibility for updating ISO processes if necessary. If implemented, any modifications must trigger automatic recalculations of dependent matrices to maintain assessment accuracy. While this feature is not part of the current design, the system architecture allows for potential future extensions to support evolving industry requirements.

- **Competencies** Data Model defines the skills and knowledge areas required for effectively performing systems engineering processes. The competencies in the system are based on the INCOSE Systems Engineering Competency Framework which have been reworked by KÖNEMANN et al[KWA+22] (Subsection: 3.2.2). Competencies in this system are categorized into distinct competency areas: Core, Socio-Personal, Managerial, and Personal. These categories ensure a structured and comprehensive evaluation of competencies across different aspects of systems engineering functions.

  Since these competencies are derived from established standards, they are considered static and require minimal modifications. As a result, the current design does

not allow for modifications (such as removing a competency from the system), and the administrator is only provided with a viewing option for transparency. This approach ensures consistency across competency assessments while maintaining alignment with industry standards.

However, the system architecture is designed with the potential for future flexibility. If customization is introduced in future enhancements, any modifications to the Competency Data Model would need to automatically propagate to all dependent matrices, including the Process–Competency Matrix and the Role–Competency Matrix and the recomputation of Role-Competency Matrix, ensuring that competency assessments remain accurate and up to date.

Role Clusters

The Role Cluster Data Model defines 14 predefined role clusters identified from the SE4OWL research project [KWA+22]. These clusters group related job roles within systems engineering, providing a structured approach to competency mapping by linking roles to relevant ISO processes and competencies. More on this is explained in the foundation section of this thesis(Subsection 3.2.1).

In the current design, role clusters are static, meaning the administrator can only view them without making any modifications. This is based on the presumption that no near future changes are expected in the Role Clusters. However, the system architecture is designed with the potential for future flexibility. Future implementation could include features to add or remove Role Clusters to the system. Any future modifications to Role Clusters would directly impact the Role–Process Matrix, which defines the relationships between roles and ISO processes. To maintain consistency and accuracy in competency mapping, such modifications would require careful management to ensure they accounts for the matrix dependencies.

Role–Process Matrix Data Model

The Role–Process Matrix is designed to support the configuration of role involvement levels in ISO 15288 processes, as defined in Section 3.2.3. By default, the system applies predefined values from KÖNEMANN et al. [KWA+22] as the standard reference for competency assessments. The system design allows administrators to configure this matrix by assigning involvement levels for each role–process combination, selecting from:

- **Not Relevant - 0:** The role does not participate in the process.
- **Supporting - 1:** The role provides assistance in performing the process.
- **Responsible - 2:** The role is primarily accountable for the process execution.
- **Designing - 3:** The role actively involves designing and improving the process.

Considering organizational requirements, the system is designed to support both individual and organization-specific competency assessments. For individual assessments, the default Role–Process Matrix is used. For organization-specific assessments, an initial matrix is generated based on default values but can be modified by administrators (together with organizational representatives) to reflect actual organizational role-process involvements.

The system is also designed to automatically recalculate the Role–Competency Matrix whenever changes are made in role-process values. This ensures that the competency assessments remain accurate and aligned with updated role process definitions. Adjustments to role-process values are applied only within the relevant assessment context, individual or organizational, to maintain consistency and adaptability in competency evaluation.

Process–Competency Matrix Data Model

The Process–Competency Matrix Data Model maps SE competencies and ISO 15288 processes, as explained in Section 3.3. It establishes the competency levels required for executing each ISO process, ensuring alignment with industry standards and organizational needs.

The SE competency assessment system is designed to allow administrators to configure this matrix by assigning competency levels for each competency–process pair, selecting from:

- **Not Useful - 0:** The competency is not required for the process.
- **Useful - 1:** The competency is beneficial but not essential for process execution.
- **Necessary -2:** The competency is critical for process execution.

By default, the matrix is pre-filled with values derived from KÖNEMANN et al. [KWA+22], ensuring consistency with established SE competency frameworks. However, administrators have the flexibility to update these values as needed.

Since the Process-Comptency Matrix directly influences the Role–Competency Matrix, any modifications made by the administrator trigger an automatic recalculation, ensuring assessments remain accurate. As the competency-to-process relationships remain consistent across organizations, this matrix is static by default and is not considered to change between organizations. This means that the Process–Competency Matrix is not organization-specific and does not vary between organizations like the Role-Process matrix.

Role–Competency Matrix Data Model

The Role–Competency Matrix Data Model is designed to define the competency requirements for each role, as explained in Section 3.4. It is derived by multiplying the Role–Process Matrix and the Process–Competency Matrix, assigning the highest competency requirement across all relevant processes:

$$Role\_Competency\_Value = \max\left(Role\_Process\_Value \times Process\_Competency\_Value\right)$$

The computed competency levels are categorized as follows:

- **0 – Not Relevant:** The competency is not required for performing the role.
- **1 – Knowing:** The role requires basic awareness and familiarity with the competency
- **2 - Understanding:** The role requires a conceptual understanding of the competency.
- **3/4 – Applying:** The competency is needed for practical application in work-related tasks.
- **6 – Mastering:** The role demands expertise and leadership in the competency.

The system is designed to automatically update the Role–Competency Matrix whenever changes are made to the Role–Process Matrix or Process–Competency Matrix, ensuring competency assessments remain accurate.

For organization-specific assessments, a custom Role-Process matrix is defined with default values from [KWA+22] whenever a new organization is added, and a corresponding Role-Competency matrix is generated for the newly added organization. Whenever the organizational-specific Role-Process matrix is modified to address the diverse role-process mapping in organizations, the corresponding Role-Comptency matrix is also recomputed. This ensures that competency mapping reflects organization-specific role definitions while aligning with industry standards.

For individual users, the system applies a default Role–Competency Matrix, based on predefined competency requirements from KÖNEMANN et al. [KWA+22], ensuring standardized competency assessments.

The system dynamically recomputes the Role–Competency Matrix in the following cases:

- When the Role–Process Matrix or Process–Competency Matrix is modified.
- When a new organization is added. A new Role-Competency Matrix is generated for this organization based on the values in the organizational-specific Role-Process matrix.

This design ensures scalability, consistency, and adaptability, allowing competency assessments to reflect real-time organizational needs while remaining structured and aligned with existing standards.

Organizational Configuration

The Organizational Configuration Data Model supports organization-specific competency models, ensuring that competency assessments reflect each organization's structure and role expectations. When a new organization is added, the system automatically generates a dedicated Role–Process Matrix, initially populated with default values from KÖNEMANN et al. [KWA+22]. The systems also automatically generate A Role-Competency matrix based on the default values in the Role-Process matrix.

To allow flexibility, administrators can modify the Role–Process Matrix in collaboration with organizational representatives, ensuring role-process associations align with actual work practices. Since the Role–Competency Matrix is derived from the Role–Process Matrix, any modifications trigger an automatic recalculation in the organizational context to maintain accuracy.

The system also distinguishes between individual users and organization-affiliated users:

- Individual users are assessed using the default Role–Competency Matrix.
- Organization-affiliated users are evaluated based on the organization-specific Role-Competency matrix.

This ensures tailored and relevant competency assessments, aligning with industry standards and organization-specific requirements.

5.3 SE Competency Assessment Survey Workflow Design

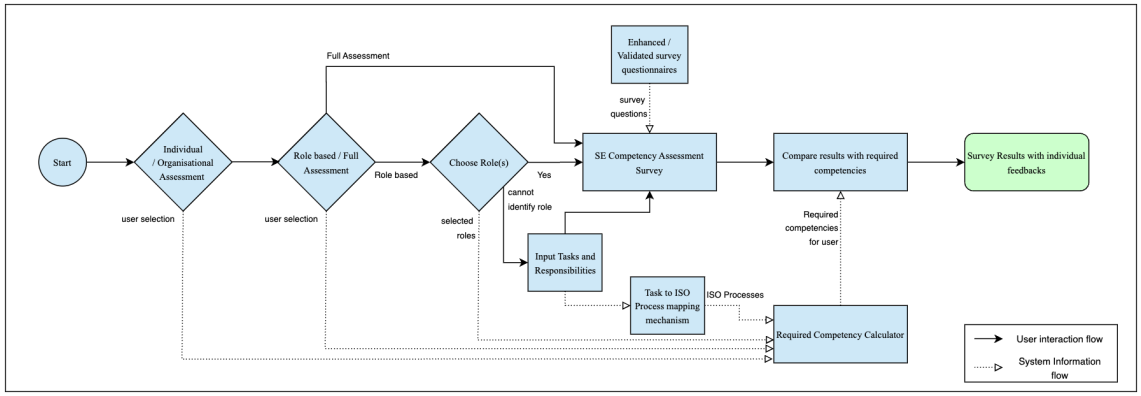

Figure 5-3: Workflow of the SE Competency Assessment Survey

Figure 5-3 illustrates the structured workflow design of the SE Competency Assessment System. It outlines the different assessment pathways available to users while taking the SE competency assessment survey. The system supports three types of competency assessments: role-based assessment, task-based assessment, and full competency assessment. These distinct survey pathways provide flexibility to users by enabling them to select the most relevant evaluation method based on their professional responsibilities and assessment goals.

The assessment begins with the user selecting whether they participate as an individual or part of an organization. This selection is passed to the Required Competency Calculator component, which calculates the survey user's competency requirements based on user selections. The Required Competency calculator uses this organization information to consider the correct organizational context when determining the target competency requirements for the user. Since different organizations may have distinct competency

expectations, this step ensures that assessments remain relevant to the user's professional environment.

Users then choose between role-based assessment and full competency assessment. In the full competency assessment, users proceed directly to the survey questionnaire, where they are evaluated across all available competencies in the system. Instead of comparing responses against predefined role requirements, the system analyzes the user's competency profile and mathematically tries to suggest the most suitable roles based on their demonstrated proficiency. This approach helps users explore roles that best match their skills and identify potential career paths.

In the role-based assessment, users select one or more predefined role clusters that align with their job roles. The Required Competency Calculator then uses this information to determine the competency benchmarks from the Role–Competency Matrix (3.4), identifying the expected proficiency levels required to perform the selected role(s). The user's competencies level recorded from the survey is then assessed against these competency requirements.

If users taking the role-based assessment cannot map their job role to any of the 14 predefined role clusters, they can opt for the task-based competency assessment. In this approach, users provide details of their tasks and responsibilities as natural language responses, categorized into responsible for, supporting, or designing. An intelligent mapping mechanism processes this information to identify the ISO processes performed by the user based on the user input. Based on these identified processes, the system derives the necessary competency requirements for performing these processes utilizing the role-process, process-competency and role-competency mappings defined in [KWA+22]. This ensures that users who do not fit into predefined role clusters receive a competency assessment tailored to their job functions.

Once the survey is completed, users receive personalized competency results. In the role-based and task-based assessments, the results compare the user's recorded competency levels with the required levels for the selected role(s) or identified performing processes. In the full competency assessment, the system identifies the best-matching roles based on the user's competency assessment by analyzing the user's competency profile and mapping it to the Role–Competency Matrix. This allows users to explore roles closely aligning with their current skill set.

The system also provides individualized feedback, offering insights into competency strengths and areas for improvement. Users can download their results, supporting further professional development planning.

From an organizational perspective, the system enables administrators to analyze competency data across the organization. Administrators can access individual scores and conduct aggregated analyses to evaluate the organization's overall competency standing. This capability helps organizations identify skill gaps, develop targeted training programs, and align workforce competencies with strategic objectives.

5.4 Design of Survey Questionnaires

The SE Competency Assessment System survey questionnaires evaluate user SE competency levels using a set of well-defined questionnaires. The questionnaires are designed using a structured, science-based approach to ensure accurate and meaningful competency measurements.

The competency levels assessed by the questionnaire align with KÖNEMANN et al. [KWA+22], applying Bloom's Taxonomy [Blo56] to classify competencies into hierarchical categories:

- **Not Relevant –** The competency does not apply.
- **Knowing –** Basic awareness of the competency.
- **Understanding –** Conceptual knowledge and explanation.
- **Applying –** Practical execution of competency in tasks.
- **Mastering –** Expertise and leadership in the competency.

To ensure structured competency level progression in questionnaires, the questionnaire uses principles from Bloom's Taxonomy [Blo56] and the Dreyfus Model of Skill Acquisition [DD80]. Bloom's Taxonomy and the Dreyfus Model organize knowledge into progressing levels, ensuring clear differentiation between competency levels.

5.4.1 Psychometric and Survey Design Principles

The questionnaire incorporates psychometric principles to enhance accuracy in competency assessment:

- **Item Response Theory (IRT)[Bak01] -** Questions are structured in increasing order of difficulty, meaning selecting a higher competency level implies proficiency in all lower levels.

- **Guttman Scaling [Eng05] –** Responses follow a hierarchical structure, ensuring logical progression in skill assessment. The questionnaire follows a structured format where respondents select from predefined hierarchical competency groups—ranging from basic (Group 1) to advanced (Group 4), with an additional *Not Relevant* option (Group 5). Although it does not use a traditional Likert scale [Lik32], it follows the principles of Guttman scaling [Eng05], ensuring that responses reflect a structured competency progression.

Additionally, the survey design also considers the common survey biases identified by Choi and Pak [CP05], and tries to minimize them.

5.4.2 Cognitive UX Considerations

To optimize usability and reduce response bias, the questionnaire incorporates cognitive UX principles:

- **Hick's Law [Hic52] –** Limits the number of response choices to minimize cognitive overload and decision fatigue.
- **Dual-Process Theory [Kah11] –** Balances intuitive (fast) and analytical (slow) thinking: Quick selections for familiar competencies and Deeper thinking needed for complex competencies levels.

By scientific approaches from psychometric principles, as well as cognitive UX techniques, the survey tries to ensure a structured, reliable, and bias-minimized competency assessment.

5.5 Key Design Considerations

The system is designed with core principles that ensure an effective SE competency assessment system. The key factors guiding the design include:

- **Scalability:** The system design can accommodate multiple organizations with distinct competency requirements. New organizations could be easily added to the system with minimal effort. The system automatically creates distinct matrices with default values to be used in the context of the newly created organization. This automated approach minimizes configuration needs and ensures seamless integration of new organizations into the competency assessment framework.

- **Flexibility:** The framework adapts to evolving organizational structures and competency needs without affecting existing competency evaluations. The design allows admins to reconfigure the role-process and process-competency mappings easily. The system would automatically identify the changes and trigger the recomputation of the Role-Competency matrix. Future-proofing measures have been considered to accommodate industry standards and business objectives changes.
- **Consistency:** Ensuring alignment with established ISO standards and competency frameworks to provide reliable and standardized assessments in different organizational contexts.
- **Usability:** The design prioritizes an intuitive and user-friendly interface for administrators and survey takers, allowing efficient management of the SE competency assessment system and easy-to-navigate survey workflow.
- **Maintainability:** The modular design allows easy configuration of the components in the SE Competency Frameworks. The design also considers the possible future improvements that might be required on the system.
- **Security:** The system does not collect personal information to assess user SE competency levels.
- **Scientific Validity of Survey Questions:** The survey design follows scientifically validated methodologies for competency assessment. The questionnaires are designed based on Bloom's Taxonomy and the Dreyfus Model to assess competency levels. Additionally, psychometric principles such as Item Response Theory (IRT) are considered to ensure accurate and structured competency evaluations. Furthermore, cognitive UX science methods are considered to reduce the cognitive overload and decision fatigue that could arise from survey question design choices. The question design also tries to minimize the common biases that could happen in the survey[CP05].

By structuring the competency assessment system around these design principles, the framework remains robust, adaptable, and capable of addressing evolving future requirements. The system architecture is intended to provide a comprehensive and scalable solution for managing and evaluating competencies in systems engineering.