E.02.11-D17-C-SHARE-Final Project Report

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Abstract

This is the final report of project C-SHARE (Joint ATM Cognition through Shared Representations), being conducted under the umbrella of the SESAR WP-E programme (first call). It contains a public summary, a list of all technical deliverables, a summary of the project's main dissemination activities (conference and journal papers), a list of total eligible costs and the primary lessons learned while running the project from the perspective of project management and support.

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Publishable Summary

SESAR WP-E project C-SHARE

A key pillar within SESAR is the introduction of Trajectory Based Operations (TBO) as a means for strategic management rather than the current tactical -hands-on- method of control. A **central role is foreseen for the human operator**, but SESAR also leans heavily upon the introduction of higher levels of automation and advanced automated support tools.

Although the introduction of higher levels of automation is not good or bad in itself, in other complex socio-technical domains this has shown to often create new problems. Examples are coordination breakdowns, skill degradation, overreliance, lack of trust, transient workload peaks, etcetera. In order to mitigate the risk for these so-called “automation surprises” or “ironies of automation”, it is essential to support joint-human automation cognition in future air traffic management systems, *by design*.

The main goal of SESAR WP-E project C-SHARE was to determine a possible “common ground” for effective human-automation coordination in 4-dimensional Trajectory Based Operations (TBO). By adopting a multidisciplinary approach, and based upon the **Cognitive Systems Engineering** (CSE) and Ecological Interface Design (EID) frameworks, a functional model of the context in which the TBO work takes place has been defined. It was hypothesized that when this same functional model supports both the cognition of the human operator *and* guides the rationale of automated agents, this enables *both* to jointly and robustly respond to any unforeseen events as team players: a **Joint Cognitive System** (JCS).

C-SHARE first aimed at developing such a functional model of the context of trajectory based operations in ATM. It was foreseen that when the ATM invariants (e.g., goals, opportunities, limitations, and the relationships between them) were captured in the model, this model can then act as a **foundation for developing transparent automation but also the human-machine interface**, and will support the human controller to remain fully in-the-loop. Furthermore, such transparency in automation was expected to facilitate a shift between various Levels of Automation (LoA), i.e., from fully manual control of individual flights to flow based management, and also supports the transition between SESAR's unmanaged and managed airspace.

One of the main outcomes of the project has been the "**shared representation**" for in-flight trajectory manipulation by ATC. This so-called 'Travel Space' representation describes a full set of re-routing possibilities for individual flights, based upon aircraft performance constraints (i.e., turn radius and speed envelope), relative locomotion with respect to other airspace users, and time-based constraints acting on the aircraft BT. The elements represented in the Travel Space follow directly from the constraints which arise from the work domain, independent of who will act on the control task, the human, the automation, or both.

As a next step, a graphical representation of the Travel Space (Figure 1) has been developed, together with an automated route advisory algorithm, both guided by the same underlying principles. This ensures that in situations where for instance the task demand load is high, the operator can request automation to quickly generate valid solution advisories that fit the mental model of the operator as supported by the graphical interface. The advisories can be quickly interpreted and effectuated by the operator. In situations where task demand load is lower, or where the controller decides to follow a certain strategy in adapting the traffic flow, the interface supports the operator to directly manipulate the traffic at hand. This joint cognitive system ensures that the operator remains at the centre of control and can decide to move back and forth between various levels of automation support.

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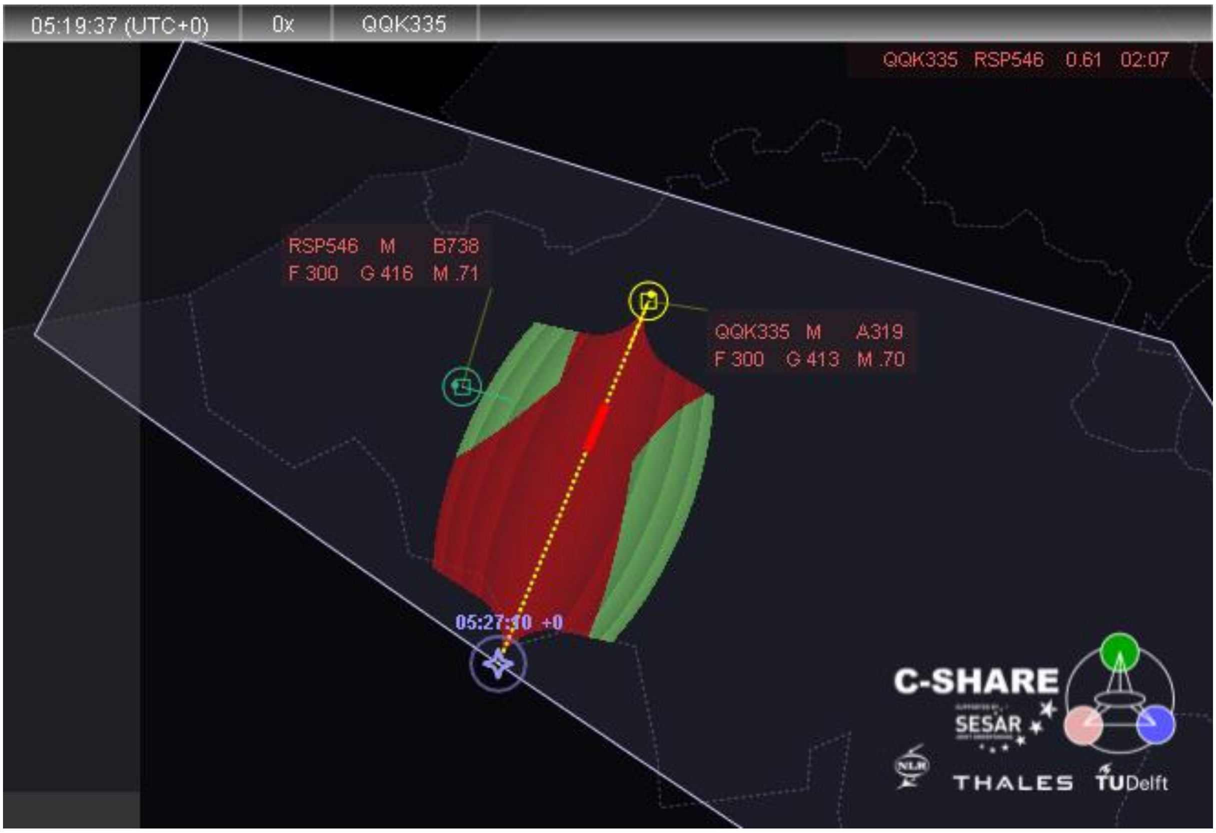

Figure 1: The C-SHARE Travel Space representation and direct-manipulation interface

A series of **human-in-the-loop experiments** and stakeholder workshops, evaluating software-based implementations of three evolving versions of the joint cognitive system, then served to validate and evaluate joint human-automation performance with such a system.

The C-SHARE iterative design and experimental process consisted of four key stages:

1) **Conceptual workshop**: The purpose of this workshop was to get valuable input and feedback about the approach taken and also the various concepts of shared representations obtained an early design phase. These concepts were in the form of both paper-based and software-based prototypes. In total, seven professionals in the field of aviation and air traffic control individually participated in a two hour interactive sessions. This workshop led to valuable additions and insights into how to develop the joint representation, and complete the first work domain analysis conducted. It also resulted in a limitation of the project scope to 3 dimensional (2 dimensions + time) TBO, and emphasizing the management of perturbations.

2) **First human-in-the-loop evaluation**: The underlying principles and usability of the Travel Space representation have been validated through a fully interactive software-based implementation. A first laboratory test was held with three domain experts (at the Eurocontrol Experimental Centre), consisted of eight scenarios with varying traffic complexity, and had the purpose to obtain qualitative feedback about the system itself. The results of this evaluation led to several adaptations to the original design, and also helped to obtain a more complete context model for the joint cognitive system, yielding an updated work domain analysis.

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3) **Main human-in-the-loop experiments**: A set of two sub-experiments have been performed, which aimed at obtaining quantitative data regarding the performance of the human-automation ensemble as a whole. The first sub-experiment presented a fully manual control task (using only the graphical Travel Space visualization), whereas the second sub-experiment provided additional automation support in the form of trajectory advisories. In total, 12 participants participated in each experiment (i.e., two times: four active ATCOs, four domain experts and four PhD students in ATM). Human factors measures and raw data from the system were recorded in six scenarios with varying airspace complexity in both experiments.

4) **Final workshop**: This workshop aimed to assess the key assets and any potential roadblocks regarding the further development of the C-SHARE concept towards readiness for operational use. The final workshop was attended by 16 participants, of whom 8 were external stakeholders from academia and industry. Overall the feedback obtained was very positive, in particular regarding the approach taken of creating a joint human-automation system rather than aiming for full automation. This is expected by all stakeholders to greatly benefit the acceptance of the developed systems by the operators who will have to use them. The limited scope of C-SHARE, however, warrants follow-up research to further develop the JCS for use in full-blown future ATM operations.

One of the main results of project C-SHARE is that, based on interviews, results of experiments, and workshops with all the main stakeholders in ATM (controllers, pilots, domain experts, industry, research establishments), the CSE-based design methodology to create a joint human-automation system has many benefits. The human operators involved will have a **deeper understanding of the actions and reasoning governing the automation**. They are not only able to see the intentions of the automated agents, they can also re-direct the machine activities more easily in occasions where they see a need to intervene.

By visualizing the task-relevant functional constraints that arise from the work-domain, the same constraints that limit automated actions, humans will get a deeper understanding of why the automation proposes that particular solution. This is expected to be **very beneficial for an operator's trust and acceptance of the automation**, and will also facilitate the transition back and from higher levels of automation (LoA). In lower Levels of Automation the visualisation of the physical constraints as advocated in C-SHARE allows controllers to decide and work upon a solution themselves; at higher levels of automation the constraint-based JCS enables the controller to better understand the automation rationale. Hence, **operator situation awareness is expected to benefit significantly across various Levels of Automation**.

In conclusion, the CSE-based design methodology to develop decision support tools as advocated by C-SHARE can greatly benefit human-automation coordination, and can indeed ensure the central role of the human operator in the future ATM system. **C-SHARE has successfully evaluated a constraint-based design approach to create a joint cognitive system**, and delivered a first prototype for re-routing aircraft in TBO to manage perturbations. More research is mandatory, however, to bring the results of C-SHARE closer to practice. It is recommended to work on extending the work domain analysis to speed manipulations, include the altitude dimension, consider possibilities to deal with streams of aircraft rather than individual aircraft, and incorporate solutions for problems that can span across sector boundaries.

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1 Introduction

1.1 Purpose of the document

The purpose of this document is to:

- Summarise the background and results of the project in the public summary.
- List all technical project deliverables;
- Summarize the formal dissemination activities;
- List all eligible costs; and
- Describe the lessons learned.

1.2 Intended readership

The intended audience for this report consists of representatives of the policymaking and R&D communities, who might have a stake in future ATM design. Those involved directly with aeronautical research, automation and HMI design and human factors might also welcome the topics covered in this report. The report is written from an engineering and experimental perspective. Those from this and related domains will probably be most familiar with the terminology, but attempts have been made to keep the document readable and approachable, to invite a wider audience.

1.3 Inputs from other projects

The C-SHARE project built on a broad body of theoretical and experimental research into ATM automation and HMI design. The vast majority of this research is publicly accessible from academia, research organisations and international conferences (primarily the SESAR Innovation Days (SID)). A new test platform for human-in-the-loop simulations was delivered in C-SHARE, allowing us to test novel 4D trajectory management HMI and automation. The C-SHARE project benefited from related projects in the WP-E programme, such as MUFASA and ADAHR.

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2 Technical Project Deliverables

As summarized in Table 1 below, C-SHARE submitted nine technical deliverables to date (excluding all deliverables that were mainly of an organizational/management nature).

SJU	Number	Title	Short Description	Approval status
D03	D1.1	Work Domain Analysis, report 1	Project approach and framework for development of the JCS, including a first functional decomposition of the work domain.	Approved
D05	D3.1	Initial Design Requirements	Overview of the initial design requirements for the functional airspace visualizations; focus on perturbation management.	Approved
D09	D2.1	Joint Cognitive System, version 0	Version '0' of the JCS, including an HMI and automated CD&R; First version of the 'travel space', and 'rapid random trees' approach to automate	Approved
D10	D1.2	Work Domain Analysis, refinement and lessons learned from the first prototype	Refinement of the WDA based on expert feedback on the first prototype of the JCS; improving the relations between the WDA and the travel space visualisations.	Approved
D11	D2.2	Joint Cognitive System, version 1	Description of the first real, *dynamic*, version of the JCS, with all initial functionalities implemented.	Approved
D12	D3.2	Intermediate Design Requirements	Results of the first HITL experiment on version 1 of the JCS are described, and refinements on the first JCS design are elaborated.	Approved
D13	D2.3	Joint Cognitive System, version 2	Description of the second and improved version of the JCS, with all refined functionalities implemented.	*Submitted*
D14	D3.3	Report about final Evaluations and Recommendations for FAV and FAR	Results of two HITL experiments are discussed which evaluated the JCS version 2 regarding their automation and HMI design characteristics.	*Submitted*
D15	D4.5	Workshop 2 minutes	The final project workshop where ATM and HMI/automation experts commented on the final JCS version.	*Submitted*

Table 1 - List of technical Project Deliverables

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3 Dissemination Activities

3.1 Presentations/publications at ATM conferences/journals

3.1.1 SESAR Innovation Days (Toulouse, Nov 2011)

Abstract

It is to be expected that the task of an air traffic controller will change with the introduction of 4D (space and time) trajectories for aircraft, as can be seen in on-going developments in ATM systems in Europe (SESAR) and the US (NextGen). However, the role of the human operator in these systems in not well defined yet. This paper presents one approach to a user-centered design for ATM based on 4D trajectory management. The design is based on Cognitive Systems Engineering (Vicente, 1999). Using a top-down approach in the analysis of the work domain, a step-wise refinement in the planning and execution of 4D trajectories is proposed. The design is described in three Abstraction Hierarchies, one for each phase in the refinement. The implications of the analysis for display design are outlined. *Foreword* – This paper describes a project that is part of SESAR Workpackage E, which is addressing long-term and innovative research. The project was started early 2011 so this description is limited to an outline of the project objectives augmented by some early findings.

Citation

Van Paassen, M.M., Borst, C., Mulder, M., Klomp, R.E., Van Leeuwen, P., & Mooij, M. (2011). Designing for Shared Cognition in Air Traffic Management. In Proceedings of the 2011 SESAR Innovation Days, Toulouse, 27-29 Nov, 2011.

3.1.2 SESAR Innovation Days (Braunschweig, Nov 2012)

Abstract

The current evolution of the ATM system, led by the SESAR programme in Europe and the NextGen programme in the US, is foreseen to bring large changes to the work domain of the air traffic controller. In both programmes, a key element is the introduction of the 4D (space and time) trajectory as a means for strategic management, rather than the current tactical – hands-on– method of control. A central role is foreseen for the human operator, aided by higher levels of automation and advanced decision support tools. However, a definite breakdown of this co-operation is not yet well defined. This paper presents one approach to the design of a shared representation for 4D trajectory management. The ultimate goal is to design a shared representation which forms the basis for both the design of the human-machine interfaces and the rationale that guides the automation. It is expected that such a shared representation will greatly benefit the joint cognition of humans and automated agents in ATM, and will also allow shifting back and forth across various levels of automation. A preliminary version of a joint cognitive representation for 4D trajectory management has been developed and is introduced in this paper. The results of a first conceptual evaluation will be discussed that aimed at validating the concept and usability of the representation. Future work will focus on the further development and refinement of shared representations by means of human-in-the-loop experiments.

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Citation

Klomp, R.E., Van Paassen, M.M., Borst, C., Mulder, M., Bos, T., Van Leeuwen, P., & Mooij, M. (2012) Joint Human-Automation Cognition through a Shared Representation of 4D Trajectory Management. . In Proceedings of the 2012 SESAR Innovation Days, Braunschweig, 26-28 Nov, 2012.

3.1.3 SESAR Innovation Days (Stockholm, Nov 2013)

Abstract

Effective joint human-automation coordination is essential in order to support the central role of the human operator in foreseen future trajectory-based air traffic operations. The SESAR WP-E project C-SHARE aims to achieve this by taking a Cognitive Systems Engineering approach, based upon accomplishing joint human and automation cognition through a shared representation of 4D-trajectory management. In foregoing research, a work domain model and a joint human-machine interface has been developed to support the human operator in the task of en-route 4D trajectory re-planning. This paper presents the findings of two experiments that aimed to determine the effect of both the initial level of traffic orderliness (i.e., structured versus unstructured traffic) and the scale of perturbations acting upon the airspace (e.g., number of conflicts and restricted areas) on the overall effectiveness of such a system. The findings of the experimental evaluation show that the C-SHARE approach to joint human-automation coordination in perturbation management is promising. Only four safety-critical events occurred during 2232 controlled flights. Further, the experiment subjects accepted the tool and found it supportive for the task at hand, resulting in a manageable degree of workload during all experiment scenarios.

Citation

Klomp, R.E., Borst, C., Mulder, M., Praetorius, G., Mooij, M., & Nieuwenhuisen, D. (2013) Experimental Evaluation of a Joint Cognitive System for 4D Trajectory Management. . In Proceedings of the 2012 SESAR Innovation Days, Stockholm, 26-28 Nov, 2013.

3.2 Presentations/publications at other conferences/journals

3.2.1 Journal of Aerospace Operations (2013)

Abstract

It is to be expected that the task of an air traffic controller will change with the introduction of four-dimensional (space and time) trajectories for aircraft, as can be seen in ongoing developments in ATM systems in Europe (SESAR) and the US (NextGen). It is clear that higher levels of automation will need to be developed to support the management of four-dimensional trajectories, but a definite concept on a distribution of the roles of automation and human users has not yet been well defined. This paper presents one approach to the design of a shared representation for 4D trajectory management. The design is based on the Cognitive Systems Engineering framework and by using a formative approach in the analysis of the work domain, a step-wise refinement in the planning and execution of 4D

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trajectories is proposed. The design is described in three Abstraction Hierarchies, one for each phase in the refinement. The ultimate goal is to design a shared representation that underlies both the design of the human-machine interface and the rationale that guides the automation. It is foreseen that such a shared representation will greatly benefit the shared cognition in ATMand allows shifting back and forth across various levels of automation. A preliminary version of a joint cognitive system for 4D trajectory management has been developed and will be introduced in this paper. Further work will focus on the refinement of the shared representation by means of human-in-the-loop experiments.

<u>Citation</u>

Van Paassen, M.M., Borst, C., Klomp, R.E., Mulder, M., Van Leeuwen, P., & Mooij, M. (2013). Designing for Shared Cognition in Air Traffic Management. *Journal of Aerospace Operations*, Vol. 2, pp. 39-51.

3.2.2 International Symposium for Aviation Psychology (Ohio, USA, May 2013)

<u>Abstract</u>

The current evolution of the ATM system, led by the SESAR programme in Europe and the NextGen programme in the US, is foreseen to bring a paradigm shift to the work domain of the air traffic controller. A focal point is the introduction of the 4D (space and time) trajectory as a means for strategic management rather than the current –hands on– method of control. In both programmes a central role is foreseen for the human operator, aided by higher levels of automation and advanced decision support tools. However, many other complex socio-technical domains have shown that the transition to higher levels of automation often introduces new problems, problems that are harder to resolve than the ones intended to solve in the first place. This paper presents one approach to the design of a shared representation for 4D trajectory management. The ultimate goal is to design a shared representation which forms the basis for both the design of the human-machine interfaces and the rationale that guides the automation. It is expected that such a shared representation will greatly benefit the joint cognition of humans and automated agents in ATM and will mitigate breakdowns in coordination by design. A preliminary version of a joint cognitive representation for 4D trajectory management has been developed and is introduced in this paper. Future work will focus on the further development and refinement of shared representations by means of human-in-the-loop experiments.

<u>Citation</u>

Klomp, R.E., Borst, C., Van Paassen, M.M., Mulder, M., Nieuwenhuisen, D., Maij, A., Mooij, M., Van Drunen, A. (2013). Designing For Joint Human-Automation Cognition Through A Shared Representation Of 4D Trajectory Management, In Proceedings of the International Symposium on Aviation Psychology (ISAP), Dayton (OH), USA, May 6-10.

3.2.3 Air Transport Operations Symposium (ATOS), (Toulouse, July 8-10 2013)

<u>Abstract</u>

To keep up with the increasing demand for air transport, new means are necessary to maintain safe skies over Europe. This paper presents the Human Factors testing results of a

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joint cognitive system that is being developed for SESARs long-term and innovative research initiatives. The joint cognitive system distributes control tasks within the ATC system over operator and automation. The system's goal is to jointly manage 4-dimensional trajectories, defined in both space and time. It provides information on areas to which aircraft can safely be rerouted to prevent perturbations without causing delays. Also, on request, the automation can advise the intended user on the best rerouting options in terms of fuel efficiency, safety, and environmental impact. Increasing levels of automation can cause surprises resulting in decreases in operator performance, such as losing situation awareness and distrusting the system. Human Factors testing can help designing an optimal cooperation between system and intended user. Therefore, this study investigated Air Traffic Controllers performing typical task activities with the new system. The results show that users are positive about the system and that it shows good potential for a future implementation after being thoroughly tested. Also, the Human Factors testing revealed aspects that need more attention to improve the system.

Citation

Maij, A., Van Drunen, A., Bos, T. & Klomp, R.E. (2013), Human Factors Testing Results of a Joint Cognitive System for 4D Trajectory Management, In Proceedings of the 4th Air Transport Operation Symposium (ATOS), Toulouse, France, July 8-11.

3.3 Demonstrations

3.3.1 C-SHARE workshop 1 (Sept. 2012)

A conceptual evaluation of the C-SHARE Joint Cognitive System was conducted. Seven professionals in the field of aviation and air traffic control were interviewed, to provide feedback on the design concepts as described in the C-SHARE D3.1. For each of these design concepts the feedback is reported in deliverable D4.4, including a summary of the main improvements for the C-SHARE Joint Cognitive System.

3.3.2 C-SHARE workshop 2 (Sept. 2013)

The final workshop of the SESAR WP-E project C-SHARE was held on September 13th 2013 at the Thales Netherlands D-CIS laboratory in Delft, The Netherlands. The workshop was attended by 16 participants, of whom 8 where external stakeholders from academia and industry with a vested interest in human-automation interaction in the context of 4D trajectory management. The workshop started with presentations about the project background and scope. After that, the participants had the opportunity to get hands-on experience with the software-based Joint Cognitive System (JCS); the human-automation ensemble designed to support effective human-automation cooperation in the course of the project. Based on this experience a SWOT-analysis has been performed to assess the systems key assets and any potential roadblocks regarding the further development of the concepts towards readiness for operational use. More details about the final workshop outcomes are given in deliverable D4.5.

3.4 Exploitation plans

Deliverable D4.6 provides an outline of the way in which the C-SHARE design approach and concepts can be industrialized. The core innovations of the project that have market

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potential are identified. As at current the status of the C-SHARE developments is at the level of concept demonstrator, a number of further improvements are briefly touched upon, which will aid in getting the C-SHARE concepts closer to market. To enhance the prospect of industrialization a number of activities have been completed, with a small number still to be performed, to increase the awareness of C-SHARE amongst various ATM stakeholders.

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4 Total Eligible Costs

Date	Deliverables on Bill	Contribution for Effort	Contribution for Other Costs (specify)	Status
15/12/2011	D0.1, D4.2, D0.2	18.862,25	0,00	Paid
19/12/2011	D0.1, D4.2, D0.2	0,00	287,50 (travel costs)	Paid
14/06./2012	D0.3, D1.1, D0.4	81.978,00*	0,00	Paid
30/09/2012	D0.5, D3.1, D4.3, D4.4, D4.6, D2.1	134.382,21*	0,00	Paid
15/04/2013	D1.2, D2.2, D0.7, D0.8	160.690,83*	0,00	Paid
18/11/2013	D0.9, D3.2, D2.3, D3.3, D4.5, D4.6, D0.9, D4.7	201.040,71*	0,00	*pending*
GRAND TOTAL		**596.954,00**	**287,50**	

Table 2 Overview of Billing (* indicates that travel costs were added to effort in these invoices)

Company	Planned man-days	Actual man-days	Total Cost	Total Contribution SJU	Reason for Deviation
TU Delft	549	633	218.975	218.975	Much more work in last six months of project than planned!
THALES	394	394	357.242	178.621	
NLR	258	258	266.194	199.645	
GRAND TOTAL	**1201**	**1285**	**842.411**	**597.241**	

Table 3 Overview of Effort and Costs per project participant

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5 Project Lessons Learnt

What worked well?
Excellent supervision by program officer Dr. Dirk Schaefer, who was always very committed and helped us improve the quality of our work, from both a content as well as a management perspective.
Much opportunities for dissemination through the SESAR Innovation Days (SID) conferences.
Size of the consortium (three members) was good. More partners make it more difficult to manage, and also could make the commitment for smaller partners low. In C-SHARE we had a good and well-balanced consortium
Good connection with the HALA! Network, good for working together and disseminate our results and approaches, in a group of young scientists and more mature research leaders.
What should be improved?
Make clear from the very start that Cost Breakdown Forms are needed; consortium members were confused as they expected this to be a fixed price (=lumpsum) tender.
Specification and invoicing of travel costs turned out to be much of a hassle, as these are not easy to predict and manage. Recommended that in the future a fixed percentage is allocated to travel costs.
It is unfortunate that there does not exist an opportunity to follow-up on a successful project. Long-term research needs more time to mature. C-SHARE could have used two more years to further develop the JCS and increase the functionality.
The short time span of these projects (30-32 months) means that in order to deliver something concrete, the scope must be small, harming a successful use of the tools and approach developed.
It is recommended that consortia and projects that deliver concrete results and that have shown to work together well get a higher chance in obtaining funding to continue their work. This stimulates consortia to better work together and deliver high-quality work.
Travel cost reimbursement should be extended to outside Europe as well. Many important conferences and research labs exist that were now impossible to visit, as these were not funded, a loss in possible dissemination and collaboration with other experts.

Table 4 - Project Lessons Learnt

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