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RESEARCH

Co-constructing safety: how air traffic controllers change goals from efficiency to safety

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Abstract
While relatively rare, air traffic control (ATC) loss of control incidents have the potential to lead to accidents with major loss of life. In such situations, controllers need to rapidly transition from efficiency to safety as the primary goal of the operation. To date, there has been relatively little investigation of how controllers collaboratively manage these goal changes (known as co-construction) in time critical safety compromised events. This paper examines whether co-construction occurs in real-time ATC collaboration and, if it does, identifies the different forms it takes and how efficiently it is conducted. 27 ATC incident occurrence reports from a major air navigation service provider that concerned a loss of separation, runway incursion, or loss of separation assurance were analysed. Each occurrence report was coded for the sequence of actions, plans, and goals, and the point at which co-construction occurred was identified. Co-constructive interactions were then classified as optimal or sub-optimal. A bottom-up thematic analysis identified characteristics of optimal and sub-optimal interactions. The analysis revealed 27 instances of co-construction. These instances of co-construction could be categorized into one of three types: Type 1 (communication about a primary goal change, N = 1), Type 2 (plan changes indexing a new primary goal, N = 13), and Type 3 (actions indexing a new plan and primary goal, N = 13). The data analysis showed that nearly half of the co-constructive interactions were suboptimal in terms of communicative efficiency. The findings suggest that controllers infer goal changes from plans and actions rather than explicitly communicating them. This lack of explicit co-construction is concerning because goal changes (e.g., prioritizing safety over efficiency) often indicate a critical system state. To enhance co-construction, we propose a formal communicative structure. This structure can be used to enhance compromised separation training, supplement occurrence investigations, and enhance future system enhancement initiatives.

Keywords Teamwork · Plans · Adaptive control · Work as done · Safety · Loss of separation

1 Introduction

The air traffic control (ATC) system is primarily designed to safely and efficiently move air traffic through discrete volumes of airspace (Biedermann et al. 2024; Langford et al. 2022). Air traffic controllers (controllers) oversee and manage the system under various operational circumstances, including normal, non-standard, and abnormal operating conditions, and cases where control is lost or aircraft separation is at risk (Friedrich et al. 2018; Kontogiannis and Malakis 2013b). Situations that deviate from standard parameters are quite common in ATC, and the system increasingly depends on the controllers'adaptive expertise, decision-making, and problem-solving capabilities to ensure safe operations. (Durand et al. 2021; Holbrook et al. 2019; Kontogiannis and Malakis 2013b). On occasions, a loss of control may lead to a loss of separation, potentially resulting in a near-miss or collision, which could cause considerable loss of life. While relatively rare, these catastrophic events become indelibly imprinted into a nation's memory. Some examples are: the runway collision at Tenerife in 1977; the runway collision at Haneda in 2024 (Japan Transport Safety Board 2024); the runway collision in Los Angeles in 1991 (National Transportation Safety Board 1991); and the mid-air collision at Interlaken in 2002 (German Federal Bureau of Aircraft Accidents Investigation (BFU) 2004).

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In the Australian ATC system (which compares favorably in occurrence rates to other world-class ATC service providers) approximately 50 controller-attributed loss of separation incidents have been reported annually for over 10 years (Airservices Australia 2020; Australian Transport Safety Bureau 2013). On average, six of these incidents each year carry the potential to escalate into catastrophic events, resulting in significant loss of life within minutes or even seconds (Airservices Australia 2020; Australian Transport Safety Bureau 2013). It is therefore vitally important to explore both why these events occur (e.g., performance problems, cognitive issues, the organizational context, and external factors) and how they are managed when they do occur (Dekker 2014; Friedrich et al. 2018; Kontogiannis and Malakis 2013b). This paper largely focuses on how controllers manage loss of control incidents during the transition from normal operating mode, where efficiency is the primary goal, to recovery mode, where safety becomes the primary goal.

1.1 The ATC system and goals

The ATC system can be characterized as a challenging, dynamic, and time-constrained system in which controllers must balance multiple, often conflicting goals (Ren and Castillo-Effen 2017; Yang et al. 2010). Two of the main goals that must be managed are safety and efficiency. Safety is an ATC goal focused on preventing collisions between aircraft or between aircraft and obstacles (International Civil Aviation Authority (ICAO) 2007). Safety is assured by planning for, establishing, and maintaining minimum spacing between aircraft or between aircraft and obstacles (e.g., 1000 feet vertically or 5 nautical miles (NM) laterally). In practical terms, safety is achieved by implementing or modifying separation standards or recovering from a loss of separation to prevent collisions. Efficiency is an ATC goal that involves processing aircraft in an orderly fashion that allows for the execution of each aircraft's flight plan, thereby minimizing both individual and accumulated system-level delays or time spent in non-optimal configurations, altitudes, or levels while facilitating the pilot's requests to the extent practicable (International Civil Aviation Authority (ICAO) 2005). The normal work of ATC involves pursuing the goal of efficiency while simultaneously assuring the goal of safety and other relevant goals, for example, noise abatement (International Civil Aviation Authority (ICAO) 2007; Oprins et al. 2006). Under normal circumstances, efficiency is usually the primary goal of ATC, with safety and other goals acting as constraints that must be satisfied (Carlson et al. 2008; National Air Traffic Services (NATS) 2019; Simon 1964). See Gyles and Bearman (2025, in preparation) for more discussion of goals, primary goals, and constraints. If the safety goal (or constraint) is threatened or compromised in the pursuit of efficiency, then the focus of work transitions such that safety becomes the primary goal rather than efficiency.

1.2 The nature of collaborative work in ATC

The ATC system, as designed, achieves its safety and efficiency goals with minimal need for interaction between controllers who manage adjacent airspace volumes. This work is formally constrained by rules, policies, and procedures that establish formal prohibitions and protections, as well as the use of standardized and systematized work processes (Corver and Grote 2016; de Jonge 2000; Morel et al. 2008). In the system as designed, goals are largely predefined offline with standardized plans and actions that implement those goals outlined in formal procedures manuals and letters of agreement (Vaughan 2021). The use of standardized plans and actions to implement previously agreed goals reflects the coordinative work of ATC (Gyles and Bearman 2017).

In addition to this coordinative work, there is a growing awareness of the often invisible ways controllers collaborate to adaptively manage the system to enhance system efficiency and safety (Andersen and Bove 2000; Kontogiannis and Malakis 2013a; Lovato et al. 2018; Malakis and Kontogiannis 2023). Recent studies reviewing inter and intra team collaborative decision making, particularly in emergency situations and in multi-team systems have identified the importance of communication exchanges that facilitate collaboration (Foster et al. 2019; Vogelpohl et al. 2020; Simona et al. 2023; Vivacqua et al. 2016). Inadequate communication exchanges during collaboration can impair goal alignment and impact the quality of subsequent communication and decision-making (Foster et al. 2019; Vogelpohl et al. 2020). This collaborative activity enables the modification of procedures, policies, and actions consistent with their original design intent to better suit local conditions (Bardram 1998; Kontogiannis and Malakis 2013b; Morel et al. 2008). Such collaboration has been defined by Gyles and Bearman (2017) as being either cooperative (when it's about plans) or co-constructive (when its about goals). Cooperative negotiation can occur using one of three different strategies: (1) deferential—where the problem is posed as a question to the second party, indicating a willingness to allow the current goals and priorities of the second party to dictate the form of the solution. (2) Preferential—where the problem and a preferred solution is posed to the second party, implying that the second party's goals and current priorities have been considered. (3) Generational—where there is an invitation to the second party to engage in a potentially protracted, generative discussion to develop and refine a mutually acceptable collaborative response (Gyles and Bearman 2017). While there is evidence for cooperation in real time ATC operations, little evidence of real-time co-construction has previously been found (Gyles and Bearman 2017). This paper delves deeper into co-construction, examining the degree to which controllers interact to change the goals of work in real time and the processes involved in this dynamic adaptation.

Gyles and Bearman (2017) have introduced a framework outlining the nature of collaborative work among controllers. This framework categorizes collaborative efforts into three levels: coordinative, cooperative, and co-constructive, based on goals, plans, and actions (Miguel 2006) (see Fig. 1). Most of a controller's work is coordinative, with established goals and plans, while the primary focus is on task execution. When a plan needs revision or a new one is necessary, controllers work cooperatively to create the new plan, after which work returns to the coordinative level. If plans cannot be adjusted or created, the work shifts to the co-constructive level, where work goals are changed. Once finished, work transitions back to the cooperative and then coordinative levels. It is crucial to understand that work does not exist solely at one level (Bardram 1998). Coordinative work exists because, at some stage, it was constructed at the cooperative and co-constructive levels. More detail regarding the theoretical origins of the framework and its use to explore collaborative work in ATC can be found in Gyles and Bearman (2017).

While theoretically, we should expect to see evidence of controllers interacting in real time to change the goals of work, to date, no evidence of this aspect of adaptive work has been observed in ATC (Gyles and Bearman 2017). In their observational study of controllers, Gyles and Bearman (2017) found evidence of coordination and cooperation but not co-construction. Assuming that co-construction is inherent in the work of ATC, there are two likely reasons why Gyles and Bearman found no evidence of co-construction. The first reason is that co-construction may be rare in the normal work conditions that typified the original research context. In normal work, the goals are stable and implicitly reflected in the policies, procedures, and work practices that shape and constrain the work.

The second reason is that co-construction focuses on goals, which are rarely explicitly discussed at work or, in fact, in many social contexts. In everyday human interactions, it is generally assumed that goals are implicitly understood from the plans or actions being discussed or observed (Baker et al. 2009; Geffner 2010; Pollack 1992; Van-Horenbeke and Peer 2021; Ying et al. 2023; Zhi-Xuan et al. 2020). As Pollack (1992) notes, you would understandably feel frustrated if, after asking for directions to a supermarket, you discovered the person had knowingly sent you to a closed store—failing to infer your goal of wanting to make a purchase. The issue of goal inference is further

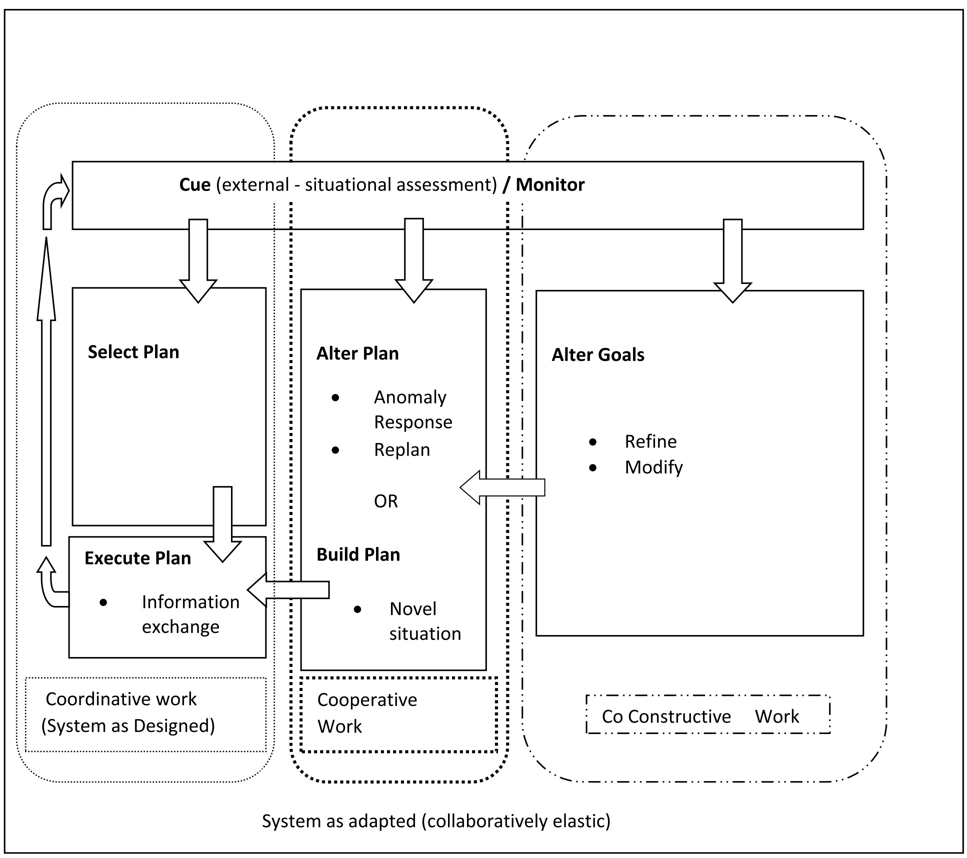


Fig. 1 Conceptual framework of collaborative work in ATC reproduced with permission from Springer Nature (Gyles and Bearman 2017)

amplified in the context of expert and proficient teams (such as those found in ATC), where more implicit forms of communication are often adopted to enhance high performance under pressure (Entin and Serfaty 1999). Overt discussions about modifying goals in ATC may often be inferred from conversations about modifications to plans and/or actions. This ability to chain backward and forward from the inferred partial and approximate goals, plans, and actions of others has been recognized as an enabler of collaborative practice offering benefits in terms of timeliness and the conservation of cognitive resources (Zhi-Xuan et al. 2020).

While this everyday practice works well for most situations, in safety critical situations, inferential chaining can be a problem because of the ambiguity and potential for misunderstanding that it entails. If the wrong goal, plan, or action is inferred, this can lead to differences in shared mental models, coordination breakdowns, and subsequent problems with the sharing and interpretation of information (Bearman et al. 2010, 2015; Lai et al. 2019, 2020). Thus, it can be critical for effective performance to use explicit information transfer even though it takes longer and is more resource-intensive. If situations are excessively complex, too dynamic, or procedurally unclear, a shift to more overt, explicit information exchange and planning is a necessary enabler of effective teamwork (Scheutz et al. 2017). Effective collaborative work is therefore likely to require a combination of implicit and explicit information exchanges (Rico et al. 2018; Scheutz et al. 2017). More importantly, in this study, given that we are investigating situations where safety margins are threatened or infringed in ATC (which emphasizes clear communication at all times) we would expect to find evidence of explicit communication regarding goal changes. Alternatively, if there is an absence of explicit communication, this may indicate an opportunity for future system enhancement (Lai et al. 2019, 2020; Rico et al. 2018; Scheutz et al. 2017).

1.3 Evidence of co-construction—3 forms

Evidence of co-construction is likely to appear in either conversations about changing primary goals (Bardram 1998) or it can be inferred from a change in plans or actions related to modifications to goals or new primary goal selection (Ying et al. 2023). Based on research regarding inferential chaining (Baker et al. 2005, 2007; Zhi-Xuan et al. 2020) three potential forms of evidence for co-construction are defined:

- Type 1—communication reflecting a change in the primary goal or a shift in goal priorities.
- Type 2—communication of plan modification or change relating to a change to the primary goal.
- Type 3—communication relating to a change in actions that indexes a changed plan related to a change to the primary goal.

While co-construction may be relatively rare during normal ATC operations, it is likely more common when safety margins (i.e., the safety goal) are threatened or breached. This requires the controller to switch primary goals from efficiency to safety. Although these are only two of the active goals for a controller (which will also include environmental concerns, orderliness, etc.), imminent or actual violations of the safety goal may represent a special case of goal tradeoff where all other goals are sacrificed in the pursuit of safety (Baron and Spranca 1997; Carlson et al. 2008; Gyles and Bearman 2025, in preparation). Analyzing these critical situations can reveal whether co-construction is a component of the real-time adaptive performance of controllers and should be included in frameworks for ATC performance (such as that proposed by Gyles and Bearman 2017).

If co-construction does occur, it's important to understand how the controllers manage these goal changes, and how effective this is. In time-critical situations where separation is compromised, co-construction must happen quickly and effectively under high-stress conditions. This is an example of a dynamic collaborative transformation (Bardram 1998). One way to explore this aspect of co-construction is to examine the related communication and action patterns between controllers to determine the effectiveness of the process.

Corradini and Cacciari (2002) have found that issues with communication exchanges can be identified by the structure of exchanges and the extent to which they comply with International Civil Aviation Organisation (ICAO) norms. Optimal transitions occur without misunderstanding, and when the exchange complies with the ICAO standard phraseologies and format (International Civil Aviation Authority (ICAO) 2007). Non-optimal transitions occur when there is a misunderstanding and there is an extra speech turn to clarify, which is then not in accordance with the standard communication format (Corradini and Cacciari 2002). In the context of goal, plan, and action hierarchies, the most effective interaction for communicating intent in an urgent situation consists of one collaborative exchange and one action (Allen and Perrault 1980; Corradini and Cacciari 2002). In a loss of separation incident, the aircraft may be seconds away from a collision, so one collaborative exchange and one action represent the optimal interaction to attempt to recover the situation. When further clarification is required or irrelevant information is provided, communication of intent is sub-optimal and will substantially increase the risk of a collision (Allen and Perrault 1980). These optimal and suboptimal co-constructive interactions can then be examined qualitatively to identify factors associated with each type. This enables us to identify ways to enhance co-construction in time-sensitive situations.

This paper explores whether we can detect real-time co-construction in ATC critical incidents and the forms it takes according to the types of co-construction identified above. If we can identify co-construction in the data, we will further analyze the characteristics of optimal and sub-optimal co-construction and recommend a strategy for improvement.

2 Method

2.1 Data

To explore co-construction in ATC, we chose a rich data set where co-construction was most likely to occur: internal incident occurrence reports produced by an ATC agency where the safety goal was at risk or was compromised. It was anticipated that these reports would provide evidence of co-construction as the primary goal shifts from efficiency to safety because of efforts to prevent collisions and re-establish separation. In ATC organizations, occurrence reports must be submitted for situations such as loss of separation[1] or loss of separation assurance[2] or Runway Incursion[3] (Airservices Australia 2024; International Civil Aviation Authority (ICAO) 2007). These reports outlined situations where there was a failure or imminent failure to maintain an adequate safety margin between two or more aircraft. Resolving these situations would appear to require a sacrificial goal tradeoff from efficiency to safety (Baron and Spranca 1997; Carlson et al. 2008; Gyles and Bearman 2025, in preparation). Analyzing the critical situations detailed in these occurrence reports makes it possible to determine whether co-construction is a component of controllers' real-time adaptive performance and, if so, what form it takes and how it is conducted.

2.2 Data extraction

231 ATC-attributed incident occurrence reports were extracted from a major air navigation service provider's occurrence reporting system database. These incidents were selected using the search terms 'Loss of Separation', 'Runway Incursion' and 'Loss of Separation Assurance' for the Occurrence Type field and 'Air Traffic Services (ATS)' for the Attribution field. Incidents with only one controller were then omitted from the dataset. Incidents involving only one controller were identified primarily by the absence of interaction with other controllers as reflected in audio transcripts. This yielded a total of 27 reports that were subject to further analysis. The reports contained transcripts of interactions between people involved in the incident (pilots, flow managers, and other controllers), supporting screenshots of traffic positions, surveillance data, and analysis. The 27 reports comprised 270 pages and represented 118 min of ATC operations. These reports represented many different operating environments (tower, approach, en route) and were from various units across the whole country.

Twenty-four of the 27 occurrence reports contained examples of co-construction, that is, evidence of at least two controllers interacting to change the primary goal. Three reports did not contain evidence of co-construction. In two of these reports, the infringement of safety margins was identified after the event, and no action was taken to recover the situation at the time of occurrence due to a lack of awareness. The other report contained a situation with a goal change and an interaction between two or more controllers. However, the goal change wasn't communicated or discussed with another controller, so there was no co-construction. Report No. 7 contained two examples of co-construction, and Report No. 19 contained three examples.

2.3 Analysis

The occurrence reports were analyzed by the first author, a qualified human factors specialist and ATC occurrence investigator with more than 35 years of experience in the en-route, approach, and tower environments. Each discrete action that occurred in the sequence of the occurrence from the start to the end was identified, and mapped to the plan that the action was designed to address and the primary goal the plan intended to achieve. Where primary goals were not explicitly stated, they were inferred from the plans and actions, and where plans were not explicitly stated, they were inferred from the actions. In all cases, the plans and primary goals were identified by the controllers' actions by an experienced air traffic controller (the first author). This data was recorded in a tabular format to retain the rich contextual complexity (see Table 1 for an example of part of this analysis). Throughout the analysis process, reference was made as required to related information in the form of maps and standard procedures for controllers and pilots (such as approach/departure procedures).

Then for each occurrence report, the point at which co-construction occurred was identified. In Tables 1, 2 and 3, the column(s) with text in italics indicates the point at which there is a transition to the new primary goal of safety. For an experienced controller, it is clear that the communication between the controllers about the goal, plans, or actions is indexing a change in the primary goal from efficiency to safety at this point. The transition point can be indicated by explicit communication. Language that would be expected in this type of situation would include 'you need to' or 'I want….' This is Type 1 co-construction. If controllers

[1] A situation where the recognized separation standard (vertical, lateral or longitudinal) between aircraft that are being provided with an Air Navigation Service Provider (ANSP) separation service is infringed.

[2] A separation standard existed, however, planned separation was not provided by the ANSP separation service.

[3] Incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft.

Table 1 Primary goals, plans, and actions showing Type 1 co-construction

Time	1515:50	1515:51	1515:52	1515:53	1516:26	1516:30	1516:38	1516:39	1516:43
Primary goal	G1 efficiency	G1 efficiency	G1 efficiency	G1 efficiency	G1 efficiency	G1 efficiency	G1 efficiency	*G2 safety/collision avoidance*	G2 safety/collision avoidance
Plan	P1 ACFT1 heading through CHARLI sequence with preceding aircraft, ACFT2 to CHARLI then planned route	P1	P1	P1	P1	P1	P1	*P2 ENR CTR requests DEP CTR resolution pending loss of separation (prevent collision and re-establish ongoing separation)*	P2 DEP CTR resolution of the pending loss of separation and establish ongoing separation
Summary—action or system state change	A1 DEP CTR hands off ACFT1 to ENR CTR. 1.1.1	A2 ENR CTR accepts ACFT1. 1.1.2	A3 DEP CTR hands off ACFT2 to ENR ATC. 1.1.3	A4 ENR CTR accepts ACFT2. 1.1.4	A5 DEP CTR instructs ACFT1 to contact the ENR CTR. 1.1.5	STCA activates ENR CTR Display ACFT1 and ACFT2 both F180 30 KNOTS (kts) closing	A6 DEP CTR starts to tell ACFT2 to contact ENR CTR (not completed). 1.1.6	*A7 ENR CTR to DEP CTR; 'I'm getting STCA on ACFT1 and 2, that are closing you need to do something before they call'. 2.2.7* *A8 DEP CTR to ENR CTR 'Yeah' 2.2.8*	A9 DEP CTR turns ACFT2 L120. 2.2.9

The portion of the table indicating co-construction is highlighted in italic

Table 2 Primary goals, plans and actions showing Type 2 co-construction

Time	1037:43	1039:08	1039:22	1041:16	1042:17	*1042:17*	*1042:26*	1042:40
Primary goal	G1 Efficiency	G1	G1	G1	G1	*G1*	*G2 safety*	G2
Plan	P1 ACFT 2 as close as practical to ACFT 1	P1	P1	P1	P1	*P1*	*P2 sight and follow ACFT 2 and ACFT 1*	P2
Summary—action or system state change	A1 APP CTR: 'ACFT 2 cancel speed restrictions, maintain current speed as long as possible, descend to four thousand'. 1.1.1	A2 APP CTR: 'ACFT 2 210 KT or greater to BRAVO'. 1.1.2	A3 APP CTR: 'ACFT 2 descend A030 CLR ILS RWY00'. 1.1.3	A4 APP CTR: 'ACFT2 contact tower XXX.X'. (ACFT 2 on FNL 11 NM and 6 behind ACFT1 70 KT closing). 1.1.4	LOS 4.9 NM longitudinal separation	*A5 APP CTR to TWR CTR: 'I've got him inside ACFT1, sorry I did miss that' TWR CTR to APP CTR: A6 ''Ahh, you've got him sighted has he?' APP CTR to TWR CTR A7: 'sorry I didn't get him sighted' 1.1.5–1.1.7*	*A8—TWR CTR to APP CTR: 'Ok I'll get him done' (advises will establish sight and follow separation.) 2.2.8*	A9 TWR CTR establishes S + F with 4.6 NM longitudinal. 2.1.2

The portion of the table indicating co-construction is highlighted in italic

don't mention the goal, but a new plan or action cannot be explained in terms of the original goal (efficiency) but can be explained in relation to a new goal (safety), then co-construction has occurred. In loss of separation or loss of separation assurance incidents, safety-related interventions are generally not compatible with efficiency, for example, they result in large turns, increases in track miles, or extra flight time. Type 2 co-construction occurs when there is a change to the plan that indexes a new goal (see Table 2; Fig. 2) and Type 3 co-construction occurs when there is a change to an action that indexes a new goal (see Table 3; Fig. 3).

The reliability of the coding process was established by having another researcher re-code a stratified random sample of 6 of the 27 sample occurrence reports (22%). The approximately 20% sample size for inter-coder reliability is consistent with established practice in qualitative research (e.g., Bearman et al. 2010, 2015; Kanoksilapatham 2015). The sample was stratified to ensure at least one randomly selected example from each type of ATC operation and a mix of short, relatively simple, and longer, more complex scenarios, and at least one example of each type of co-construction, including an example with no co-construction. The stratification was designed to ensure that a representative range of occurrence reports was coded. The inter-coder reliability analysis resulted in a Kappa of 0.8, representing a good agreement level (Lombard et al. 2002; McHugh 2012).

2.4 Optimality of co-constructive interactions

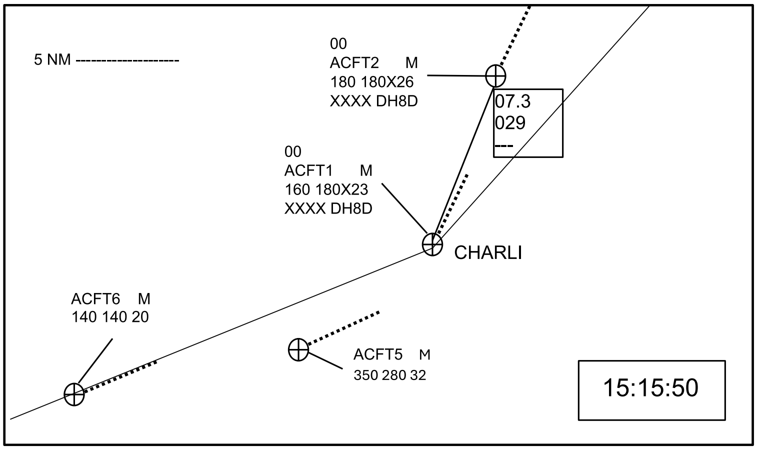
To investigate the process and efficiency of co-construction, the co-constructive interactions of controllers were examined in more detail. In the context of goal, plan, and action hierarchies, the most effective interaction for communicating intent in an urgent situation consists of one collaborative exchange and one action (Allen and Perrault 1980; Corradini and Cacciari 2002). Therefore, the coordinative exchanges were coded as optimal or sub-optimal based on the number of coordinative exchanges and actions. Optimal co-construction consisted of one collaborative exchange (with one statement and one response) and one action (see Fig. 8 for an example). Sub-optimal co-construction involves more than one collaborative exchange and/or more than one action (see Fig. 9 for an example). This coding scheme was used because in loss of control situations where the safety margins are at risk or compromised, time is critical. Controller interactions in those circumstances must be clear, concise, and timely if separation is to be reestablished promptly and the risk of midair collision is to be minimized. The optimal and sub-optimal co-constructive interactions were then qualitatively analyzed using a bottom-up thematic analysis to determine factors associated with either optimal or sub-optimal interactions. The different factors that characterized

Table 3 Primary goals, plans and actions showing Type 3 co-construction

Time	0356:58 and 0357:18	0400:31[a]	0400:36 and 0400:39	0400:41 and 0400:43	0400:45	0400:47	0401:07	0401:12
Primary goal	G1 Efficiency	G1	G1	G1	G1	G1	G2 safety	G2
Plan	P1 TWR CTR sep ACFT1 RWY YY and ACFT2 (incorrectly believed RWY XX)	P2 proposed—break off ACFT1 early from practice approach (TWR CTR identifies conflict seeks confirmation from APP. At 0400:21 the 2 ACFT are 5.7 nm apart)	P1	P3 take ACFT1 out of the sequence	P3	P3	P4 TWR CTR assesses ACFT1 requires further turn and stop climb to expedite divergence from ACFT2	P4
Summary—action or system state change	A1 APP CTR: 'ACFT2 cleared visual approach' 1.1.1 A2 APP CTR: 'ACFT1 cleared VOR approach RWY YY' 1.1.2	A3 TWR CTR to APP CTR: 'Do you want me to break ACT1 off or do you think he's going to stay in front of ACFT2'. 1.2.3	A4 APP CTR to TWR CTR: 'I thought ACFT2 was RWY XX, my fault actually'. 1.1.4 A5 TWR CTR to APP CTR: 'They're both on my frequency, actually'. 1.1.5	A6 APP CTR to TWR CTR: 'Can you break off ACFT 1 now'. 1.3.6 A7 TWR CTR to APP CTR: 'What heading would you like him on?' 1.3.7	A8 APP CTR TO TWR CTR: 'Put him on a heading of 360'. 1.3.8 A9 TWR CTR to APP CTR: '360 Roger'. 1.3.9	A10 TWR CTR to ACFT1: ACFT1 cancel approach, turn left heading 360 visual'. 1.3.10	A11 TWR CTR to APP CTR: 'ACFT1 left heading 330 and maintain two thousand'. 2.4.11	A12 APP CTR to TWR CTR: 'Concur ACFT1 left heading 330, maintain two thousand'. 2.4.12

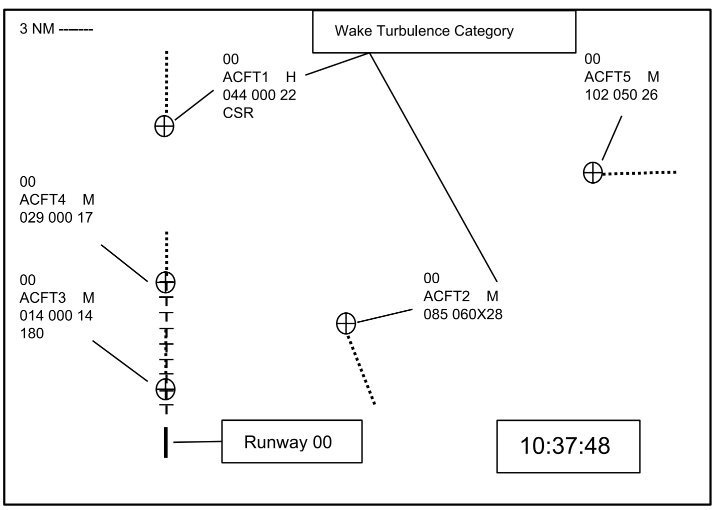
The portion of the table indicating co-construction is highlighted in italic

[a]Interactions time stamped 0400:31 to 0400:47 were time-stamped collectively in that period in the original investigation. Indicative timings for discrete interactions are estimated based on an even distribution



1515:51 ENR CTR accepts jurisdiction of ACFT1.
1515:52 DEP CTR hands-off ACFT2 to ENR CTR.
1515:53 ENR CTR accepts jurisdiction of ACFT2.
1516:26 DEP CTR instructs ACFT1 to contact ENR ATC ON XXX.X.
1516:30 STCA activates between ACFT1 and ACFT2 on display.
1516:38 DEP CTR commences instruction for ACFT2 to contact ENR CTR. The instruction is not completed.
1516:39 ENR CTR: "*I'm getting STCA on ACFT 1 & 2 that are closing you need to do something before they call*"
DEP CTR: "Yeah"
1516:43 DEP CTR: "ACFT2, turn right onto, correction, left onto the heading of one two zero"
ACFT2: "Left heading one two zero, ACFT2"

Fig. 2 Position of ACFT1 and ACFT2 when ACFT 1 was handed off from DEP CTR to ENR CTR and transcript extract. The portion of the transcript indicating co-construction is highlighted



1037:43 APP CTR: 'ACFT2 cancel speed restrictions, maintain current speed as long as possible, descend to four thousand'

1039:08 APP CTR: 'ACFT2 210KT or greater to BRAVO'.

Fig. 3 Position of ACFT1 and ACFT2 and transcript extract. Label indicates the display of wake turbulence category for each aircraft. *H* heavy, *M* medium. Aircraft 3, 4 and 5 are incidental to this analysis

optimal and sub-optimal co-construction were therefore generated from the data in a bottom-up way.

3 Results

In the 27 examples of co-construction, there was 1 example of Type 1 co-construction, where controllers verbalized the need for a change of primary goal. There were 13 examples of Type 2 co-construction, where there was overt communication of plan modification relating to a change in primary goal. There were 13 examples of Type 3 co-construction, where there was communication relating to a change in actions that index a changed plan related to a change in primary goal. Three separate examples are provided below, each describing a different type of co-construction.[4]

3.1 Three types of co-construction

Below are three different examples of co-construction, showing Type 1, Type 2 and Type 3 co-construction. First, a general overview of each scenario is provided, followed by a more detailed elaboration of how the co-construction occurred. Additional context in the form of amplifying

[4] To protect the identity of the individuals and companies involved in the occurrences callsigns, waypoints, position report names, times, runway identifiers, and locations were anonymized.

comments for these examples can be found in Supplemental Information (available online).

3.1.1 Type 1 co-construction

Type 1 co-construction represents a situation with communication about the need to change to a new primary goal. In this example (Report No.20), the primary goal shifts from efficiency (Goal 1) (which was based on minimizing track miles and aircraft delay) to safety (maintain separation) (Goal 2).

Figure 2 shows the aircraft's relative positions[5] and an extract from the occurrence transcript leading up to the co-constructive event. Table 1 describes a section of the analysis of primary goal, plans, and actions coded for this occurrence, proximate to the co-constructive activity. Both aircraft in this scenario are De Havilland Dash 8–400 turboprops (DH8D's). At approximately 30nm from the departure aerodrome, the primary goal of efficiency (Goal 1) was being pursued, with the plan (Plan 1) being for aircraft 1 (ACFT1) and then aircraft 2 (ACFT2) to pass through position CHARLI. At 1515:50, the departure controller (DEP CTR) handed ACFT1 off to the en route controller (ENR CTR) (Action 1), which was accepted at 1515:51 (Action 2). The DEP CTR hands off ACFT2 to the ENR CTR at 1515:52 (Action 3), which was accepted at 1515:53 (Action 4). At 1516:26, the DEP CTR instructs ACFT1 to contact the ENR CTR (Action 5). At 1516:30, the short-term conflict alert (STCA) was activated on the ENR CTR's surveillance display. At 1516:38, the DEP CTR tells ACFT2 to contact the ENR CTR, but the instruction is not completed (Action 6). At 1516:39, the ENR CTR contacts the DEP CTR, saying,'I'm getting STCA on ACFT 1 and 2 that are closing, you need to do something before they call'(Action 7). The DEP CTR acknowledges this with 'Yeah.' (Action 8). In this exchange, the ENR CTR communicates to the DEP CTR the need to shift from efficiency as the primary goal to safety. This new primary goal requires a new plan (Plan 2) to be implemented whereby the DEP CTR will maintain separation and a new action (Action 9), which involves instructing ACFT2 to turn to diverge from ACFT1. At 1516:43, the DEP CTR carries out Action 9 by instructing, 'ACFT2, turn right onto, correction, left onto the heading of one two zero.' The applicable separation minima was 5 nautical miles (NM) and the minimum separation achieved was 5.2NM.

3.1.2 Type 2 co-construction—plan amendment indexes primary goal change

Type 2 co-construction can be inferred from communication relating to a change to a plan that indexes a different primary goal. In the following example (Report No.12), plans designed to achieve the primary goal of efficiency change to plans designed to achieve the primary goal of safety.

Figures 3, 4 and 5 show the aircraft's relative position and an excerpt from the occurrence transcript. Table 2 describes a section of the analysis of primary goals, plans, and actions coded for this occurrence. Our analysis starts at 1037:43. At this point, the system is operating as designed and the primary goal was to maximize sequence efficiency (Goal 1). The current plan was to establish ACFT1 (an Airbus A330-200), which is a Heavy wake turbulence category aircraft, and ACFT2 (De Havilland Dash 8–400), which is a Medium wake turbulence category aircraft not less than 4nm apart by radar on final (which is consistent with the Approach Controller's (APP CTR) erroneous belief that ACFT1 is in the medium wake turbulence category) (Plan 1). Consistent with this plan, at 1037:43, APP CTR canceled the speed restrictions on ACFT2 to reduce the separation between ACFT2 and ACFT1 (Action 1). At 1039:08, APP CTR further tightened the sequence and reduced the spacing between ACFT2 and ACFT1 by instructing ACFT2 to maintain speed at 210KTS or greater to position BRAVO (ACFT1's current position) (Action 2). At 1039:22, APP CTR instructed ACFT2 to descend to A030 and cleared them for an Instrument Landing System[6] (ILS) approach (Action 3). At 1041:16, the APP CTR told ACFT2 to call the Tower Controller (TWR CTR) (Action 4). Separation continued to reduce to the incorrect target of 4nm, and at 1042:17, when the aircraft was at 4.9nm, a loss of separation (LOS) occurred.

APP CTR subsequently recognized that ACFT1 was a heavy wake turbulence aircraft and, at 1042:17, advised TWR CTR of their error, stating, 'I've got him inside ACFT1, sorry I did miss tha' (Action 5). At approximately 1042:20, the TWR CTR asked APP CTR if they had established a 'sight and follow' procedure: 'Ahh, you've got him sighted, has he?' (Action 6). This is the only means of reducing the separation below the required 5nm wake turbulence separation spacing and the quickest means of reestablishing

[5] Each aircraft is represented by a circular symbol containing a cross with a series of small dots representing its historical track. The first line of the attached label if displayed includes the arrival or departure runway, e.g. 00. The second line indicates aircraft callsign and a symbol reflecting Heavy, Medium or Light wake turbulence category (H, M or L). The third line contains actual level, followed by controller assigned level and the last two digits reflect current ground speed as a factor of 10, i.e., add a 0 to the last two digits to reflect actual ground speed. The fourth line includes destination and aircraft type if displayed and the fifth line is a free text area for controller annotations.

[6] Instrument Landing System is defined as a precision runway approach aid based on two radio beams which together provide pilots with both vertical and horizontal guidance during an approach to land (Eurocontrol, n.d.).

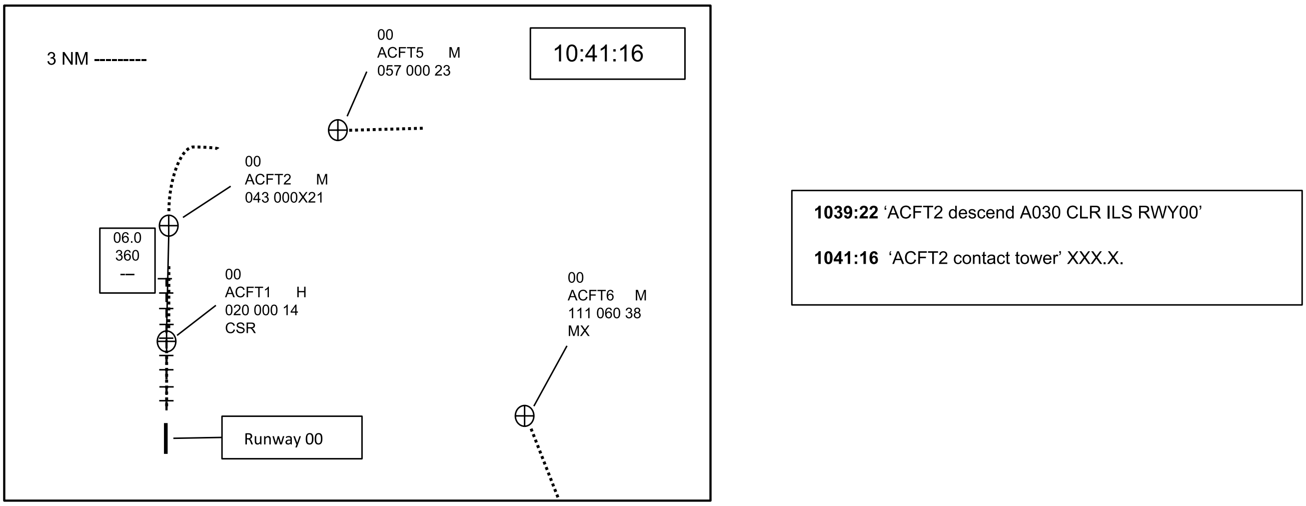


Fig. 4 Spacing ACFT 1 and 2 when ACFT2 turned onto final when instructed to contact the TWR CTR with transcript extract

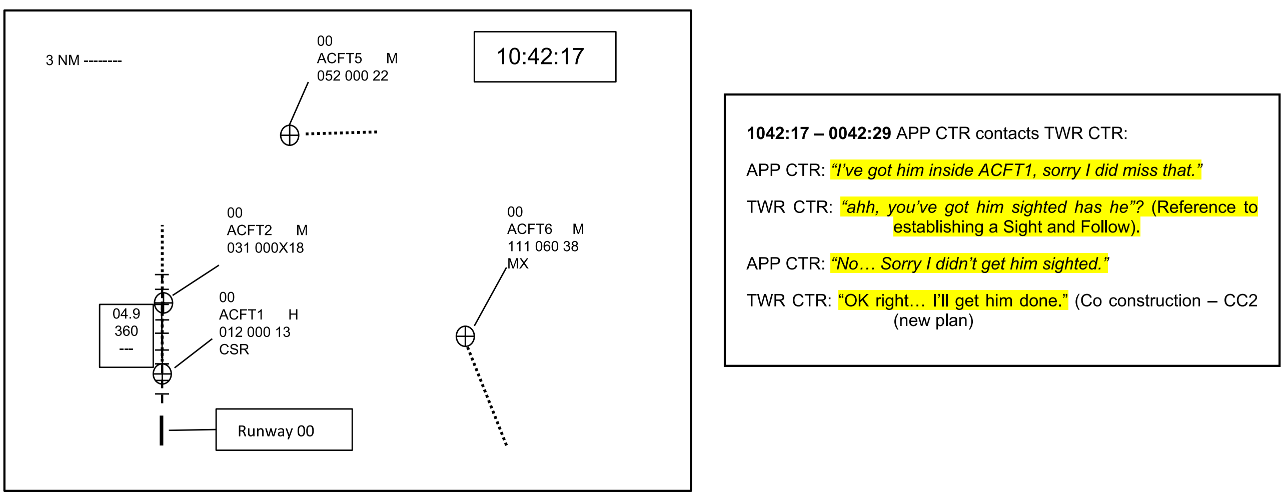


Fig. 5 ACFT 1 and 2 5 NM longitudinal separation infringed and transcript extract

separation. At approximately 1042:23, APP CTR confirmed that he didn't do this, 'No… Sorry I didn't get him sighted' (Action 7). At 1042:26,[7] the TWR CTR stated that he would establish sight and follow, 'OK right… I'll get him done.' (Plan 2 'Sight and Follow' and Action 8). This exchange between APP CTR and the TWR CTR changed the plan for the aircraft from establishing ACFT1 and ACFT2 not less than 4nm apart by radar on final (Plan 1) to 'sight and follow' (Plan 2). TWR CTR actions this at 1042:40 (Action 9). This indicates that the primary goal had changed from maximizing sequence efficiency (Goal 1) to ensuring safe operations (re-establish separation) (Goal 2).

3.1.3 Type 3 co-construction—action change indexes primary goal change

Type 3 co-construction occurs when there is communication relating to a change in actions that indexes a changed plan related to a new primary goal. In the following example (Report No.15), one of the controllers suggests an action related to a new plan to increase the divergence between two aircraft to avoid a collision, changing the primary goal from efficiency to safety.

[7] This time was estimated as the original report transcript simply indicates that Actions 5 to 8 occurred in the period 1042:17–1042:29. The timing of action 8 was estimated by having a controller verbalize the transcript so that an approximate time for action 8 could be estimated.

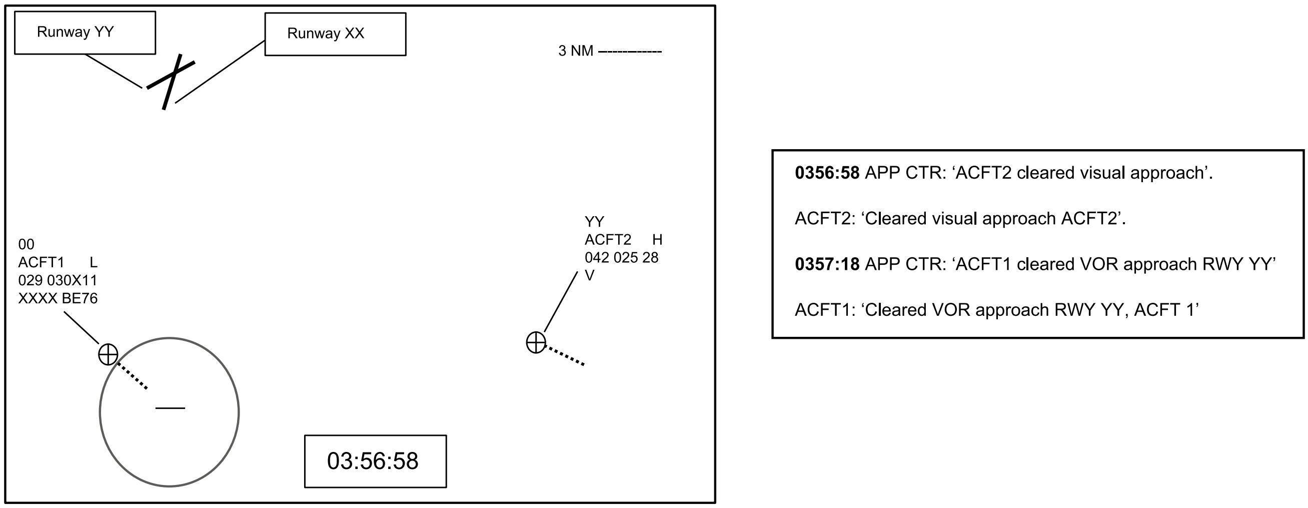


Fig. 6 Position of ACFT1 and ACFT2 when the APP CTR clears ACFT2 for the visual approach and transcript extract

Figures 6 and 7 show the aircraft's relative position and transcript, and Table 3 describes a section of the analysis of primary goals, plans, and actions coded for this occurrence. Our analysis starts at 0356:58 when the approach controller (APP CTR) cleared ACFT2 (a Boeing 737–800) for a visual approach, 'ACFT2 cleared visual approach' (Action 1). At this point, the primary goal was to maximize sequence efficiency (Goal 1). The plan was for ACFT1 (a Beechcraft 76—a light twin training aircraft) to conduct a practice instrument approach (VOR approach) to RWY YY and overshoot, and the mistaken belief that ACFT2 would land runway XX with the tower providing visual separation between the overshooting ACFT1 and the landing ACFT2 if required (Plan 1). At 0357:18 APP CTR cleared ACFT1 for the practice approach RWY YY, 'ACFT1, cleared VOR approach runway YY' (Action2).

At 0400:31, the tower controller (TWR CTR) questioned the spacing between the two aircraft, asking the APP CTR, 'Do you want me to break off ACFT1 early or do you do you think he's going to stay in front of ACFT2?' (Action 3). At this point, the primary goal was still efficiency with the TWR CTR presenting the APP CTR with two different plans. Plan 2 was to have ACFT2 follow ACFT1 into Runway YY. Plan 3 removed ACFT1 from the sequence. This query triggered the APP CTR's realization that their belief that ACFT2 was landing on Runway XX was incorrect. At 0400:36 they told the TWR CTR, "I thought ACFT2 was for Runway XX, my fault" (Action 4). The TWR CTR advised the APP CTR that both aircraft were now on their frequency (Action 5). At 0400:43, the APP CTR asked the TWR CTR to remove ACFT1 from the sequence, saying, "Can you break ACFT1 off now" (Plan 3, Action 6). At approximately 0400:41, the TWR CTR2 asked the APP CTR the exact action they should take to execute that plan, "what heading would you like him." (Action 7). The APP CTR advised, "Put him on a heading of 360" (Action 8). The TWR CTR acknowledged the instruction '360, roger'. (Action 9). The TWR CTR instructed ACFT1 to cancel their approach and turn left 360 visual (Action 10). At this stage, the primary goal was still based on efficiency (Goal 1) with the (mistaken) belief that the safety goal would continue to be achieved (i.e. separation existed and would continue to exist). The plan selected by the APP CTR was to remove ACFT1 from the sequence and re-sequence them behind ACFT2 (Plan 3) on the initial heading of 360. At this point, if the primary goal was safety, it would be normal practice to remove the second aircraft in the sequence or alternatively to take positive action with ACFT1 to assure separation by issuing a radar vector and establishing vertical separation with ACFT2.

At 0401:07, the TWR CTR suggested to the APP CTR that ACFT1 needs a wider heading of 330 and that it should maintain 2000 ft (rather than continue climbing so that the aircraft's speed can increase, further increasing the rate of divergence between ACFT1 and ACFT2), (Action 11). At 0401:12, the APP CTR concurred with these suggestions (Action 12). At this point, it was clear that the TWR CTR had determined that the current plan (Plan 3) would not maintain the separation standard, and something needed to be done. Action 11 and 12 clearly refer to a new plan of maximizing the rate of divergence between the two aircraft (Plan 4) and a shift in the primary goal to maintaining safety (re-establish separation) (Goal 2).

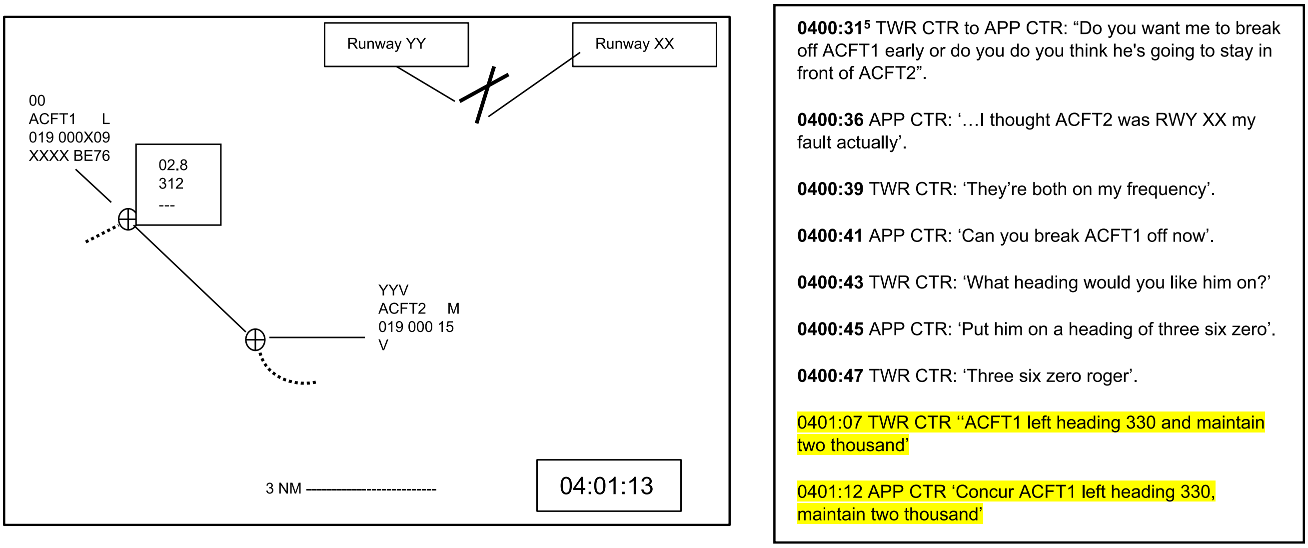


Fig. 7 Position of ACFT1 and ACFT2 when the minimum required separation of 3 NM was infringed and transcript extract

3.2 Optimal and sub-optimal co-constructive interactions

The number of actions and collaborative exchanges in the dataset were coded to examine co-construction communicative efficiency. Co-constructions that involved one action and one interaction were labeled as optimal interactions; co-constructions with more interactions than this were labeled as sub-optimal. It can be seen from Table 4 that 52% (13 of 25) of the co-constructions were coded as optimal, with 56% (14 of 25) coded as sub-optimal. When co-construction is considered by Type, slightly more co-constructions that involved interactions about actions but not plans (Type 3) were optimal (54%). In contrast, most co-constructions involving interactions about plans (Type 2) were sub-optimal (62%).

The co-constructive interactions were then analyzed to determine factors associated with optimal and sub-optimal interactions. Optimal co-constructions were often associated with one or more of the following elements:

- clear and succinct communication of the triggering situation, required actions, or conditions to be met
- the use of actions that have supporting documented procedures (e.g. using the Go Around procedure)
- automated alerting that is accessible to all parties highlighting a critical situation
- shared and accurate understanding of the situation or the other party's intentions

For example, Fig. 8 contains the following co-constructive example from Report 20, which is considered to be optimal (1 collaborative exchange and 1 action).

Sub-optimal interactions were often associated with one or more of the following elements:

- failure to clarify the situation/context accurately for the other party
- the provision of a request with an inadequate or incomplete qualifying statement, which triggered the need for further clarification
- the provision of extraneous information not relevant to the management of the current situation
- lack of shared understanding of either the situation or the intentions of the other party
- provision of extraneous information indirectly related to the current situation. e.g.blame

Figure 9 shows an exchange that is considered to be sub-optimal.

4 Discussion

This study first sought to determine whether real-time co-construction occurs in ATC. Co-construction, defined as an interaction between controllers to change the goals of work,

Table 4 Type of co-construction by optimality

	Total	Optimal	Sub optimal
Type 1	1	1	0
Type 2	13	5	8
Type 3	13	7	6
Total	27	13	14

Fig. 8 Example of optimal co-construction communicative exchange

ENR ATC: I'm getting a STCA on ACFT1 and 2 that are closing, you need to do something before they call'. DEP: ýeah'. **(Collaborative exchange 1)**

DEP: ACFT2 turn right, correct, left onto heading of 120'. **(Action 1)**

was theorized by Gyles and Bearman (2017) to occur during real-time ATC operations. However, their research did not reveal any supporting evidence of co-construction. By examining a range of situations in which co-construction was most likely to occur (situations involving actual or imminent loss of separation), we found that co-construction does take place in real-time in ATC. In the 27 occurrence reports from the sample dataset, 27 instances of co-constructive work were identified. These instances of co-constructive work can be classified into three categories: Type 1 involves communication about the need to change the primary goals; Type 2 involves communication about plans related to altered primary goals; and Type 3 involves communication regarding a change in action that signifies a modified plan connected to altered primary goals. These findings confirm that there are real time interactions between controllers to change the goals of work, which supports the inclusion of co-construction in collaborative ATC frameworks, such as the one proposed by Gyles and Bearman (2017).

Surprisingly, only one instance of Type 1 co-construction was identified, where a change in the primary goal was directly communicated. The other 26 instances of co-construction were classified as Type 2 or Type 3, with the primary goal change conveyed indirectly through discussions about altered plans or actions. Given that the incidents examined in this study concerned loss of control situations where the aircraft may be seconds from a collision it was expected that there would be clear and direct communication about the primary goal shift from efficiency to safety. Instead, the goal shift tended to be inferred from plans and actions, which introduces ambiguity and potential for misunderstanding. In a well-managed safety system like ATC that emphasizes clear communication at all times, it was anticipated that significant changes in the system's operating mode (from efficiency to safety) would be explicitly conveyed (Peterson et al. 2001). For example, when aircraft are subject to grave and imminent danger and require immediate assistance, this situation is communicated to ATC and coordinated between controllers using standard phraseologies, which include explicit acknowledgment using the keyword 'MAYDAY.' (Airservices Australia and Department of Defence 2024). The use of key or trigger phrases is a core element of standard ATC coordination, as it serves as a prime, providing context to the receiver regarding the message's content, format, and priority, which expedites and enhances the quality of information exchange. However, no standard phraseology or keywords have been defined to highlight critical goal changes during ATC coordination that do not pertain to aircraft priority changes (such as MAYDAY).

There is a clear need to formally recognize and manage this communicative aspect of collaborative work to increase transparency (Scheutz et al. 2022). High levels of transparency enhance the listener's ability to accurately infer the originator's intent and reasoning, reducing the likelihood of misunderstandings by aligning goals and planned actions. This type of communication should endeavour to be accurate, informative (say no more than required), relevant and brief, orderly and avoid ambiguity (Grice 1975). Based on these guidelines and our analysis of optimal and suboptimal co-construction, we propose a structured approach to guide controllers involved in co-construction. The syntax of these phrases has been structured to mirror the format of the current standard ATC phraseologies. An initiating controller must first explicitly flag that an imminent goal change will occur using a standard trigger word or phrase, such as 'safety alert.' This indicates to the other controller that they should expect to operate in a different mode from their current operation. Next, there must be clear and concise communication regarding the triggering situation, the required actions or conditions to be met, and the urgency of the action, for example, 'compromised separation, ACFT1 and ACFT2, turn ACFT2 right heading 090 immediately.' Utilizing actions that have documented supporting procedures (e.g., the Go Around procedure) is preferred when applicable, as they clearly convey the revised plan and goal. Statements likely to trigger further communication and the provision of irrelevant, extraneous information (such as,"It's not my fault") should be avoided in managing the situation.

This study has several potential limitations. The source data consists of occurrence reports created by investigators based on their interpretations of what occurred. Although our analysis primarily derives from the included screenshots and transcripts rather than the investigators' conclusions, there remains a possibility that the evidence in these reports was selected to align with the investigators' narrative. Consequently, the resulting analysis may not fully reflect the actual events. This is a common issue when investigating secondary reports of this nature. Another potential limitation is that the data set was analyzed by a single researcher (the first author), which may introduce inaccuracies and biases in the analysis. The first author's 35 years of experience in

Fig. 9 Example of sub-optimal co-construction

TWR CTR asked the APP CTR, "Are you happy with that intercept reference wake turbulence?" APP CTR replied, "could be light or medium." **(Collaborative exchange1).** TWR CTR stated, "light." APP CTR asked, "how is that going to work" **(Collaborative exchange2).** TWR CTR attempted to establish a 'Sight and Follow' procedure **(Action1),** APP CTR asked TWR CTR to reduce ACFT to minimum speed **(Collaborative exchange3**). TWR CTR reduced ACFT to min speed **(Action2)**. TWR CTR issued a wake turbulence caution **(Action3)** and then sent ACFT around **(Action4).**

ATC is likely to reduce misunderstandings and inaccuracies in the analysis, and the intercoder reliability analysis offers some reassurance that another researcher can consistently code at least part of the data. We have also incorporated as much relevant information from the transcripts and screenshots as possible in our results, enabling readers to judge our conclusions.

5 Conclusion

The findings of this study, support Gyles and Bearman's (2017) theory of ATC collaboration by demonstrating that controllers do engage in real-time co-construction in ATC. At the same time, this study has significantly deepened our understanding of how co-construction is conducted, some of the problems with this process, and how it could be improved. Three types of co-construction could be identified: Type 1, where there is communication about a primary goal change; Type 2, where a plan change indexes a new primary goal; and Type 3, where actions index a new plan and primary goal. This advances the theory of co-construction and provides a basis for further research into this topic.

The study has also shown that in ATC loss of control incidents, co-construction tends to be conducted through inferences based on changes to plans and actions, rather than through explicit communication. From a theoretical perspective, this shows that co-construction is largely implicit and that people tend not to explicitly talk about goals and goal changes, even in relation to safety critical events. From a practical perspective, this provides an opportunity to enhance safety by providing a more explicit formal process for indicating goal transitions. Making the process more formal and explicit will help to reduce ambiguity and the potential for misunderstanding. Based on our analysis of optimal and sub-optimal co-construction interactions, we were able to make recommendations about how this can be done.

In high-pressure and time-sensitive scenarios, wherein co-construction is critical, applying effective communication techniques may determine whether separation standards are upheld or compromised, thereby preventing potential aircraft collisions. Consequently, from an organizational perspective, it appears highly probable that implementing standard protocols and procedures to facilitate explicit and timely communication regarding co-construction, particularly in instances where safety margins are compromised or endangered, will result in significant advantages. This initiative would extend direct support to operational personnel compelled to negotiate co-construction in time-critical and safety-sensitive environments, significantly enhancing their adaptive capacity.

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Declarations

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